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Individual Differences in Night-Vision Efficiency

M. H. PIRENNE, F. H. C. MARRIOTT
and E. F. O'DOHERTY

With a section on 'The Frequency of Seeing at Low Illumination'

by H. K. Hartline and P. R. McDonald

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1957

MEDICAL RESEARCH COUNCIL

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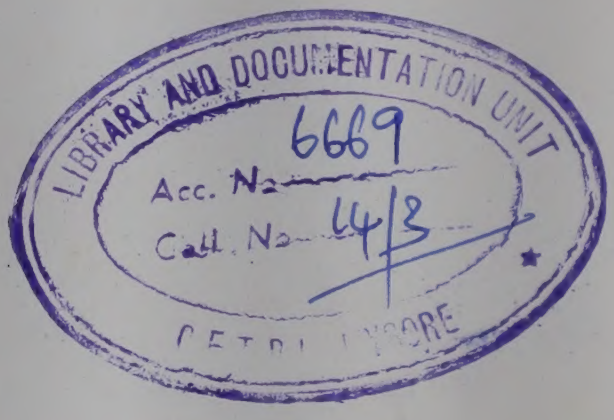

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PREFACE

THE experiments described in this Report were initiated during the Second World War in the Medical Research Council's Applied Psychology Research Unit at Cambridge, under the direction of Professor Sir Frederic Bartlett. They formed part of a research project on vision carried out on behalf of the Council's Military Personnel Research Committee, which had been set up in consultation with the War Office in 1941. The immediate aim was to make a comparative study of the many tests that had been devised for the selection of military personnel for tasks requiring high visual performance at night; this developed into a laboratory investigation in which the salient features of the main types of tests were examined. After the war the work was continued because of its intrinsic interest for the study of human vision, special attention being paid to the relation of the quantum properties of light to retinal excitation.

The main problem underlying the investigation was the assessment of the part played by sensory acuity in perception, the latter, at the human level, being recognized as a function of intellectual factors as well as of the sensory receptor system. Earlier workers had drawn attention to the relevance of such factors as education, experience, and familiarity; but while they were agreed on the importance of a low visual threshold value, they felt unable to evaluate the relative significance of the qualities and abilities that make for high visual performance in the dark.

In the experiments described in this Report the aim of the authors was to make assessments of sensory acuity and of perceptual efficiency by means of specialized visual tests administered at low illuminations to dark-adapted subjects. Without denying the general relevance of intellectual factors, they conclude that, at the threshold of vision or near it, differences in perceptual efficiency between one individual and another arise mainly from differences in sensory acuity. They suggest that this finding may be important both in theory and in practice: in theory it implies that at or near the threshold, perception and sensation must have an almost identical meaning, and in practice it means that in the selection of personnel for high night-vision efficiency a low threshold is a deciding factor. The experimental measurements also indicate the extraordinary efficiency of the human eye over a wide range of luminances, in terms of the light energy required for its functioning.

MEDICAL RESEARCH COUNCIL,
38 Old Queen Street,
London, S.W.1.

February 18th, 1957

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Acknowledgements are due to Professor H. K. Hartline and Dr. P. R. McDonald for kindly permitting their report, "The Frequency of Seeing at Low Illumination", to be published here; also to the Syndics of the Fitzwilliam Museum, Cambridge, for permission to reproduce the print facing page 32, and to *The Times* and to Ilford Ltd. for permission to quote passages from their publications.

We also wish to thank Professor A. V. Hill for his encouragement of this visual research over many years, Dr. W. S. Stiles, Dr. B. H. Crawford, and other members of the National Physical Laboratory for their unfailing help with regard to the practical and theoretical problems involved, and Miss D. Clark and Mrs. A. Watson for their assistance in preparing the manuscript for publication.

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INDIVIDUAL DIFFERENCES IN NIGHT-VISION EFFICIENCY

Introduction

THIS is a study in a problem which has far-reaching theoretical and practical consequences. The relation between sensory acuity and perceptual ability is a curiously complicated one, because perception at the human level is a function of intellectual factors as well as of the sensory receptor system. Nevertheless, it is not correct to conclude at once that perception is not related, in terms of perfection of performance, to the level of sensory acuity; it is the conclusion of the present study that, allowing for the importance of the 'internal' psychological process, perceptual ability is positively correlated with sensory acuity.

The problem of the relation between the two factors varies at different levels of performance. Thus the experience of an expert in painting who visits the National Gallery is radically different from that of someone who has never before looked at pictures, even though the latter may have much better sight than the former. This is not the sort of problem we are concerned with here; neither are we concerned with the particular problems of form perception. Specifically, we are concerned with perceptual ability at very low light intensities. In a sense, however, all perception is form perception, though near or at the threshold it may be very difficult to say what form is perceived.

In all situations where an attempt is made to reach the physiological limits of an organism the measurements become quite difficult for the subject and require a good deal of intelligence of a particular kind. Whether in practice the measurements are more reliable and accurate in one situation than in another depends upon all sorts of considerations and each case must be examined separately.

I. Visual Acuity and the Absolute Threshold: First Series of Experiments

AIMS

The aims of this part of the investigation were:
(a) to discover the distribution of visual acuity at various luminance levels, from the lowest visible luminances to the luminance of a moonlit sky, in a population of young, trained subjects; and
(b) to determine the correlation between the acuity at each luminance level and the absolute light threshold measured by the special method of fixation and flash. By suitable training of each subject it was attempted to reach a performance which could not be improved further and which, it was hoped, would thus correspond to the limit set by the sensory equipment of each subject.

APPARATUS

The apparatus consisted of a source of light, L, which illuminated a screen, O, of opal glass (Fig. 1); this screen constituted the field of view of the subjects. A number of black screens (not shown in Fig. 1), pierced with suitable holes, were placed between L and O in order to exclude extraneous light. Test objects, T, such as black Landolt rings could be hung in front of the screen, facing the subject, for the measurement of visual acuity (Fig. 2*a*, p. 3). The whole screen could also be blacked out by a diaphragm, except for a central circular opening which then provided a small field for the measurement of the absolute light threshold by the fixation-and-flash method (Fig. 2*b*, p. 3).

Light Source

The source of light was a 12 V, 12 W electric lamp with opal bulb, run at an accurately controlled voltage of 11·2 V. The lamp had been aged for 150 hours at 12 V.

A portion of this lamp was diaphragmed by an open circular window, 19 mm. in diameter, in the metal box containing the lamp (Fig. 1). A Compur photographic shutter was mounted in front of this window. Immediately in front of

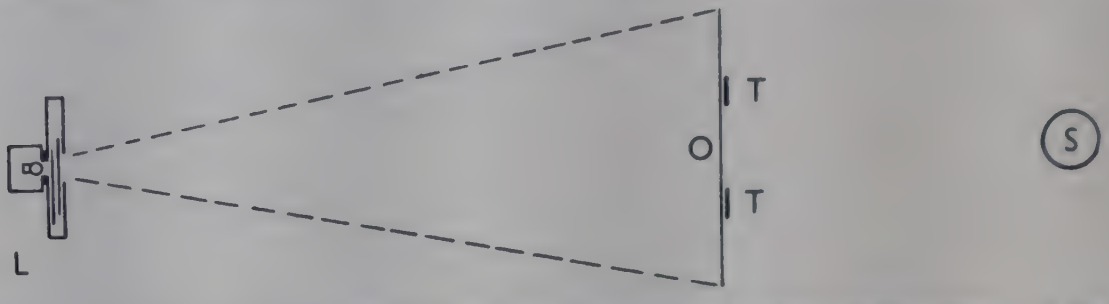

FIG. 1. Diagram (plan) of apparatus used in the visual acuity experiments. L = source of light, in light-tight box, with shutter and wedges. O = illuminated screen, TT = test object, S = position of subject's head.

the shutter two neutral wedges (Ilford, colloidal carbon in gelatine, cemented in Canada balsam between glass) were mounted in such a way that they could be moved independently using a rack and pinion. Each wedge was about 25 cm. in length and had attached to it a millimetre scale by means of which its position in front of the lamp could be defined. A 1 mm. displacement of either wedge corresponded to a change in optical density of about 0·01, the total range of intensity covered by the double wedge system thus being approximately 4·5 logarithmic units. The optical density is, as usual, defined as the negative logarithm, to base 10, of the fraction of light transmitted,

$$\text{density} = \log^* \frac{I}{I_t} \qquad (1)$$

I being the incident light intensity and I_t the intensity transmitted.

The box containing the lamp was light-tight, and any light which came out of it had to pass through the Compur shutter and through the wedges. Special care was taken to ensure that no light could pass round the wedges or their mounting; if $\frac{1}{1000}$ part of the light from the lamp, for instance, had leaked round the wedges, this would have nullified the experimental control of the lower intensities, for, at optical densities higher than 3, the wedges themselves transmit less than $\frac{1}{1000}$ part of the light emitted by the lamp. No inconsistencies attributable to such leakages of light have been observed in the many experiments made over a number of years using this apparatus.

In constructing the apparatus special care was taken to ensure its stability and reliability. The time variation of the candle-power of the lamp was checked at intervals. This was done by visual photometric comparison of the apparatus lamp with a similar lamp reserved exclusively for this purpose, and the intensity of which could be regarded as constant since it was used only for brief periods at rare intervals.

Field of View

Visual acuity: measurement of the C *thresholds.* The screen, O, was mounted in front of the light source, and at a fixed distance of 242 cm. from it. It consisted

* 'Log' in this Report always means 'logarithm to base 10'.

of a vertical circular sheet of flashed opal glass 1 m. in diameter (Figs. 1 and 2*a*). This screen subtended an angle of 47° at the eye of the subject. Regions outside this circle were permanently in darkness.

The test objects, some of which were mounted on clear plastic disks, were suspended in the centre of the glass screen, 2 cm. from the glass, on the side furthest from the lamp. Thus when the shutter was opened the subject could see the opaque test object silhouetted in black against the illuminated field (Fig. 2*a*).

The colour temperature of the lamp was measured by comparison with a lamp calibrated by the National Physical Laboratory and was found to be 2440° K. According to measurements made at the National Physical Laboratory, this colour temperature was reduced by about 40° after the light had passed through the opal screen. Thus the colour temperature of the light reaching the subject was 2400° K.

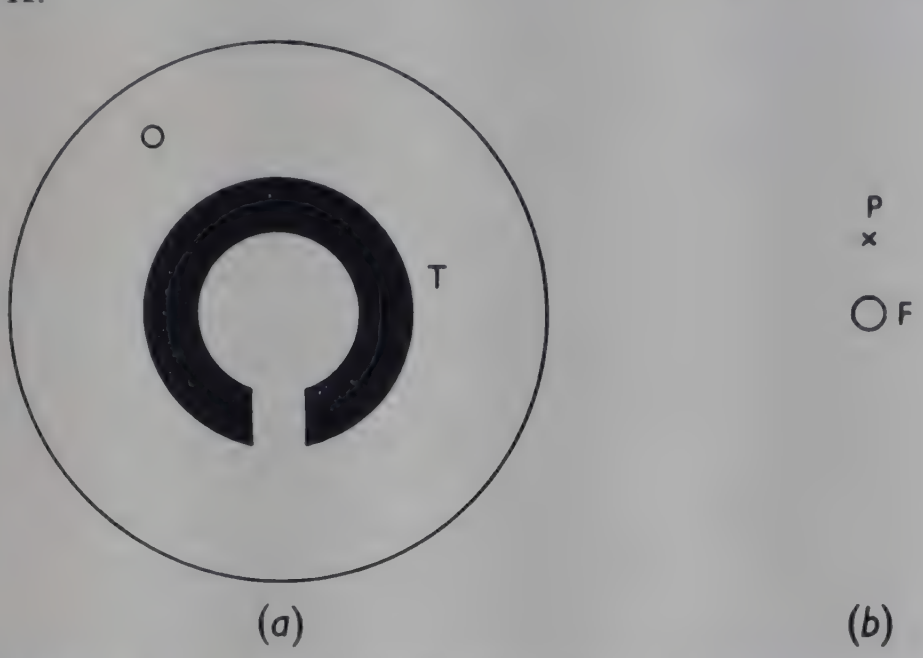

FIG. 2. Field of view of subject during measurements of (*a*) the C thresholds (Fig. 1) and (*b*) the flash threshold.
(*a*) C test object (T) in 'down' position silhouetted against illuminated circular screen (O) (the particular object shown is the 295′ C).
(*b*) Field (F) to be illuminated by flash, and fixation point (P).

The luminance of the large field of opal glass when the wedges were taken out of the beam of light was measured by the National Physical Laboratory. It was equal to 0·0148 foot-lambert (ft.-L.)*. This is equal to $0{\cdot}0148 \times 3{\cdot}426 = 0{\cdot}0507$ candela/m². The Laboratory also measured the effective transmission factor of the plastic disk, mounted 2 cm. from the opal screen, which was found to be 86·3 per cent.

The optical density of the wedges was also measured by the National Physical Laboratory. By moving the wedges it was therefore possible to adjust the luminance of the screen to any chosen value within the range of the instrument. (As a result of the fact that the wedges were not quite neutral, the spectral distribution of the light became altered to some extent, particularly at low luminance levels. See Appendix B, p. 67.)

The subject sat in an armchair on the side of the screen away from the lamp, leaning his head on a chin rest. The height of the chair and of the chin rest could be adjusted in such a way that the subject, sitting in comfort, had his eyes in front of the middle of the screen at a distance of very nearly 114·6 cm. from

* This unit was formerly known as the equivalent foot-candle.

the test object. At this distance a 2 cm. length on the screen subtends an angle of 1° at the eye. The subject thus saw a circular field whose diameter subtended 47° at his eye, and silhouetted against this uniformly lit background he saw the test object (Fig. 2*a*).

The absolute threshold measured by fixation and flash. For measuring what, for the purposes of this Report, will be called the 'flash threshold' of the subjects, the glass screen was entirely covered by an opaque diaphragm, except in the centre, where a circular field 3° in diameter was left visible. The Compur shutter mounted in front of the lamp allowed the light of the source to be flashed for durations of $\frac{1}{5}$ sec. on this small field, the luminance being as usual controlled by the neutral wedge system. A red fixation light was placed 7° above the centre of the 3° field (Fig. 2*b*). The subject adjusted its intensity by means of a variable resistance, so as to keep it just comfortably visible. An opaque screen provided with a suitable hole and an eyepiece was placed above the chin rest for these measurements, which were made uniocularly.

Test Objects for the Acuity Experiments

For the visual acuity experiments, instead of measuring the acuity value of a subject at given luminance levels, the luminance necessary to enable the subject to see in turn each of a series of test objects was determined. The logarithms to base 10 of these luminance values will be called the 'C thresholds' in this Report. Landolt international test objects were used: C's or broken circles in which the width of the ring and of the gap is one-fifth of the total outside diameter of the letter (Fig. 2*a*). Acuity is defined as the reciprocal of the angle, in minutes of arc, subtended at the eye by the width of the gap in the smallest broken circle whose orientation could be detected by the subject. On this scale 'normal' acuity as defined in ophthalmological practice is equal to unity. (The second line of Table 2 (p. 9) gives the minimum acuity needed to recognize at a distance of 114·6 cm. the C test objects used in this investigation.) These various test objects will be referred to by the angle, in minutes, subtended at the eye of the subject by the width of the gap in the broken ring. The values of this angle are given in the column headings of Table 2. Thus the 24′ C, corresponding to acuity $\frac{1}{24}$, had a diameter of 4 cm. and its gap, 8 mm. wide, subtended 24 minutes of arc at the eye.

Eight Landolt C test objects were used. The six smaller C's—the 96′, 48′, 24′, 12′, 6′, and 3′ C's—were accurately made of brass and blackened by chemical treatment. They were attached to clear plastic disks 32 cm. in diameter by plastic cement. The 295′ C and the 191′ C were made of black cardboard and were hung directly, that is, without plastic disks. The test objects could be hung in four definite positions, the gap of the C facing up, down, right, or left. Since they were interposed between the illuminated screen and the eye of the subject, they presented the greatest possible contrast to the screen.

SUBJECTS

The 22 subjects—19 men and 3 women—were all aged between 18 and 22 years, except for Subject 1, a woman of 30. This subject gave results close to the mean of the other subjects, so that the difference in age was here of no importance. All the subjects belonged to university circles and most of them were medical students. They had volunteered for these long experiments and it seemed clear that they were doing their best.

The visual acuity of the subjects under daylight conditions had first been tested using Landolt C's. They all had an acuity equal to 0·7 or more for each

eye. Subjects who ordinarily wore spectacles were not excluded, provided their acuity with spectacles reached this level; they wore their spectacles during the experiments.

METHODS

One subject was tested at a time. After the subject had been adapted to complete darkness for at least half an hour, the 'flash threshold' was measured with one eye, using the natural pupil, as explained below. Then the whole 47° field was exposed and the thresholds of visibility of the different C test objects (C thresholds, as defined above) were determined binocularly, one after another, as explained below (p. 6), beginning with the largest C. On some occasions the measurements began with the smallest C at the higher luminances, and ended with the flash threshold, no significant difference being found between the results of the two methods. The time the subjects spent in the dark before any measurements were taken—half an hour or more—should in practice have ensured complete dark adaptation in normal subjects, even though a much longer time may be required in the case of vitamin A-deficient subjects (Hume and Krebs, 1949).

The Flash Threshold

The flash threshold was determined in the following way. Looking through the eyepiece, the subject fixed his gaze on the red fixation point and signalled by tapping that he was ready. The experimenter then immediately operated the shutter, thus flashing the light for $\frac{1}{5}$ sec. on the 3° field placed 7° below the fixation point. The subject reported whether he had seen the flash or not. This constituted one trial. The subject did not attempt to maintain fixation permanently; he was instructed to relax between trials and to bring his gaze back on to the fixation point for each individual trial.*

By repeating the above process at various wedge settings chosen by the experimenter, the flash threshold, defined as the logarithm of the luminance at which the subject would see the flash in 50 per cent of the trials, was determined. This was done either by systematically recording an approximate frequency-of-seeing curve in terms of luminance and reading on the log luminance scale the value corresponding to 50 per cent on the frequency-of-seeing curve, or by a more rapid method in which the experimenter performed an essentially similar process without writing down each result. The intensity steps between adjacent wedge settings were in general 0·1 log unit. 'Blanks' were mixed with the actual light exposures, that is, sometimes the shutter was opened while, unknown to the subject, an opaque screen was intercepting the light from the lamp. The greater number of the subjects never answered 'seen' when presented with a blank. Five subjects did so, however, for a fraction of the blanks. For these five subjects the threshold was estimated mostly by extrapolating from the part of the frequency curve where the frequency was over 75 per cent. It was not generally attempted to obtain threshold values with an accuracy corresponding to less than 0·05 log unit.

In general the right eye was used for the flash threshold measurements, unless the left eye was the master eye—being used in preference to the right, for instance, in microscope work. In a number of cases where the thresholds of both eyes were determined, no significant difference was found except in Subject 8; in this

* The theory and practice of the fixation-and-flash method used in this investigation are discussed in Appendix A.

subject the difference was 0·15 log unit and the mean for the two eyes was taken as the threshold.

In these flash threshold measurements, as in those later ones (p. 18) which were made according to the method of Hartline and McDonald (Appendix C). the subject was kept in ignorance of the 'nominal' intensities, that is, the intensity values, recorded on the scale of the instrument, of the flashes presented to him; and, of course, the subject did not know when the 'stimulus' was a blank. This is considered an important point (Pirenne and Marriott, 1955); it will be discussed at greater length in a paper now in course of publication (Pirenne and Marriott, 1958).

The C Thresholds

The field used in the acuity measurements provided a large surround of approximately the same brightness as the background on which the test object was shown. This condition is known to be favourable to accurate acuity measurements (Lythgoe, 1932); it also approximates to the conditions to be found in observing the night sky. Illumination of the screen was continuous, and the time allowed to the subject for giving an answer was left rather indefinite.

A given C test-object was presented in four positions, that is, with the gap facing up, down, right and left, in random succession. The field luminance was changed in steps of 0·1 log unit. The luminance at which the subject judged correctly the position of the test object three times out of a series of four trials was taken as the threshold of visibility for this particular C.

The subjects were familiar with the shape of the test objects and with the four possible positions in which they might appear. They were encouraged to give an answer when they had even the faintest impression that the test object was in a certain position. During the course of the first series of experiments the experimenter, standing beside the subject in front of the screen, gave thorough individual instruction to each subject on how to look.

As the test objects presented became successively smaller, the part of the retina giving the highest acuity moved towards the fovea, but did not reach the foveal centre even in the case of the smallest test object used here, namely the 3′ C. For the larger test objects, the most effective part of the retina was far into the periphery. (Mandelbaum and Sloan (1947) have measured the variation of acuity with light intensity in various retinal regions, using a fixation-and-flash method; their results are of obvious interest in the present connexion.)

It was found that training at each acuity level was required in order to ensure that the subject always chose the best part of his retinae. Such a choice is more or less subconscious. Related experiments (Crawford, 1947) have shown that a given subject can be quite consistent in making this choice, though the faculty is not usually developed without instruction and experience.

The power of concentrating the attention had a considerable effect on the results. This effect, which is difficult to distinguish from the effect of training, is similar to that observed in visual photometry (Walsh, 1953). In clinical measurements it is known that the apparent visual acuity of a patient can increase as much as twofold when his powers of concentration are fully brought to bear on his task (Landolt, 1904). It was important, therefore, to keep the subjects keen and interested during the experiments; care was also taken to make them comfortable and to avoid fatiguing them, by allowing short periods of relaxation.

In one series of measurements the average number of trials for each C was twelve. One whole series, including dark adaptation, lasted two hours. To ensure

as complete a training as possible a second series was carried out on all the subjects on another day; and yet a third series was carried out on all but four subjects. Only the results of the last series made for each subject were taken into consideration. Each figure in the results represents one threshold determination for one subject; there has been no averaging of measurements taken on different days.

The measurements for the 3′ C, the smallest test object used, correspond to the highest luminance levels and lie at the extreme luminance range of the apparatus. They were included because they give indications about the trend of acuity at higher luminance levels, but they may be less reliable than measurements made at lower levels.

RESULTS

The results of the experiment are given in Table 1. This table also shows the age and sex of the subjects, how many series of measurements were carried out

TABLE 1

Results of first series of experiments: measurements of flash and C *thresholds in* 22 *subjects*

ıbject no.	Age (yrs.)	Sex	How many series of measurements carried out	Uni-ocular flash threshold	Binocular C thresholds							
					295′ C	191′ C	96′ C	48′ C	24′ C	12′ C	6′ C	3′
1*	30	F.	2	$\bar{6}\cdot46$	—	—	$\bar{6}\cdot06$	—	—	$\bar{5}\cdot67$	$\bar{4}\cdot73$	$\bar{3}\cdot$
2	19	M.	3	$\bar{6}\cdot41$	—	$\bar{7}\cdot41$	$\bar{7}\cdot86$	$\bar{6}\cdot25$	$\bar{6}\cdot87$	$\bar{5}\cdot50$	$\bar{4}\cdot99$	$\bar{3}\cdot$
3*	19	M.	3	$\bar{6}\cdot52$	$\bar{7}\cdot61$	$\bar{7}\cdot72$	$\bar{7}\cdot96$	—	$\bar{6}\cdot87$	$\bar{5}\cdot67$	$\bar{4}\cdot99$	$\bar{3}\cdot$
4	19	M.	3	$\bar{6}\cdot41$	$\bar{7}\cdot51$	$\bar{7}\cdot61$	$\bar{7}\cdot96$	—	—	$\bar{5}\cdot29$	$\bar{4}\cdot68$	$\bar{3}\cdot$
5	19	M.	3	$\bar{6}\cdot57$	$\bar{7}\cdot72$	$\bar{7}\cdot82$	$\bar{6}\cdot06$	—	$\bar{6}\cdot77$	$\bar{5}\cdot57$	$\bar{4}\cdot89$	$\bar{3}\cdot$
6	20	M.	3	$\bar{6}\cdot31$	$\bar{7}\cdot39$	—	$\bar{7}\cdot96$	—	$\bar{6}\cdot77$	$\bar{5}\cdot50$	$\bar{4}\cdot47$	$\bar{3}\cdot$
7	22	M.	3	$\bar{6}\cdot72$	$\bar{7}\cdot77$	—	$\bar{6}\cdot15$	$\bar{6}\cdot66$	$\bar{5}\cdot08$	$\bar{5}\cdot88$	$\bar{4}\cdot99$	$\bar{3}\cdot$
8*	18	M.	3	$\bar{6}\cdot61$	—	$\bar{7}\cdot87$	$\bar{6}\cdot15$	$\bar{6}\cdot56$	$\bar{5}\cdot18$	$\bar{5}\cdot83$	$\bar{4}\cdot99$	$\bar{3}\cdot$
9	21	M.	3	$\bar{6}\cdot62$	$\bar{7}\cdot77$	—	—	—	$\bar{5}\cdot03$	$\bar{5}\cdot78$	$\bar{4}\cdot99$	$\bar{3}\cdot$
10*	21	M.	2	$\bar{6}\cdot51$	$\bar{7}\cdot66$	$\bar{7}\cdot72$	$\bar{6}\cdot16$	$\bar{6}\cdot42$	$\bar{6}\cdot99$	$\bar{5}\cdot84$	$\bar{3}\cdot06$	$\bar{3}\cdot$
11	21	M.	4	$\bar{6}\cdot31$	$\bar{7}\cdot51$	—	$\bar{7}\cdot86$	—	$\bar{6}\cdot66$	$\bar{5}\cdot18$	$\bar{4}\cdot68$	$\bar{3}\cdot$
12*	20	M.	3	$\bar{6}\cdot72$	—	$\bar{7}\cdot82$	$\bar{6}\cdot31$	—	$\bar{5}\cdot25$	$\bar{4}\cdot04$	$\bar{4}\cdot95$	$\bar{3}\cdot$
13	18	M.	2	$\bar{6}\cdot41$	—	$\bar{7}\cdot61$	$\bar{7}\cdot86$	—	$\bar{6}\cdot66$	$\bar{5}\cdot67$	$\bar{4}\cdot89$	$\bar{3}\cdot$
14	19	F.	3	$\bar{6}\cdot46$	$\bar{7}\cdot51$	$\bar{7}\cdot66$	$\bar{7}\cdot86$	—	—	—	$\bar{4}\cdot78$	$\bar{3}\cdot$
15	18	M.	3	$\bar{6}\cdot62$	$\bar{7}\cdot61$	$\bar{7}\cdot72$	$\bar{6}\cdot06$	—	$\bar{5}\cdot29$	$\bar{4}\cdot08$	$\bar{3}\cdot30$	$\bar{3}\cdot$
16	18	M.	3	$\bar{6}\cdot52$	—	$\bar{7}\cdot82$	$\bar{6}\cdot05$	—	—	$\bar{5}\cdot67$	$\bar{4}\cdot89$	$\bar{3}\cdot$
17*	21	M.	3	$\bar{6}\cdot93$	$\bar{6}\cdot11$	$\bar{6}\cdot21$	$\bar{6}\cdot56$	—	$\bar{5}\cdot39$	$\bar{4}\cdot17$	$\bar{3}\cdot20$	$\bar{3}\cdot$
18*	18	M.	3	$\bar{6}\cdot62$	$\bar{7}\cdot61$	—	$\bar{6}\cdot15$	—	$\bar{5}\cdot08$	$\bar{5}\cdot88$	$\bar{4}\cdot83$	—
19	19	F.	3	$\bar{6}\cdot41$	$\bar{7}\cdot51$	$\bar{7}\cdot61$	$\bar{7}\cdot96$	—	$\bar{6}\cdot98$	$\bar{5}\cdot67$	$\bar{4}\cdot78$	$\bar{3}\cdot$
20*	19	M.	3	$\bar{6}\cdot62$	$\bar{7}\cdot72$	$\bar{7}\cdot82$	$\bar{6}\cdot05$	—	—	$\bar{5}\cdot67$	$\bar{4}\cdot99$	$\bar{3}\cdot$
21*	20	M.	3	$\bar{6}\cdot52$	$\bar{7}\cdot61$	—	$\bar{6}\cdot06$	—	$\bar{6}\cdot98$	$\bar{5}\cdot57$	$\bar{4}\cdot99$	$\bar{3}\cdot$
22*	19	M.	2	$\bar{6}\cdot57$	$\bar{7}\cdot61$	$\bar{7}\cdot82$	$\bar{7}\cdot86$	—	—	$\bar{5}\cdot78$	$\bar{3}\cdot10$	$\bar{3}\cdot$

* Subjects with spectacles.

Note: The threshold values given here are the logarithms, to base 10, of luminances measured in foo
amberts. Add 0·535 log unit to convert into candelas per square metre; add 0·032 to convert in
nillilamberts.

on them, and whether they wore spectacles. The results given are:—

(1) The value of the binocular threshold of each of the Landolt test objects placed in the centre of the continuously lighted 47° field. This value is expressed as the logarithm, to base 10, of the luminance of the large field at which the

subject judged correctly the position of the C in approximately three out of four different trials. As has already been mentioned, these logarithmic values will here be referred to simply as the 'C thresholds'. For example, the C threshold for the 3′ C for Subject 1 was $\bar{3}{\cdot}51$; this means that at a screen luminance of 0·0032 ft.-L. this subject reported correctly the position of the C test object in approximately three out of four trials.

(2) The value of the uniocular absolute threshold corresponding to the 3° field placed 7° below the fixation point, and exposed in flashes of 0·2 sec. duration. The table gives the logarithm of the luminance at which the subject sees the flash in approximately half the trials. Such logarithmic values will be referred to as 'flash thresholds'. Thus the flash threshold of Subject 1 was $\bar{6}{\cdot}46$; this means that this subject saw the light flash in about half the trials when the screen luminance was 0·000 002 9 ft.-L.

All luminances are expressed in foot-lamberts. One foot-lambert (equivalent foot-candle) is equal to 3·426 candelas per square metre (cd/m²) or nit, or to 1·0764 millilamberts.

It will be noted that for most of the subjects the flash threshold is about 1 log unit *higher* than the threshold for the 295′ C, the largest test object (cf. Fig. 3, p. 10). This is partly due to the fact that the flash threshold is measured using a small field and a short exposure, while the threshold for the C is measured using a much larger field and a 'continuous' exposure, that is, in practice, an exposure of many seconds. Again, a retinal location 7° from the fovea does not generally correspond to the highest retinal sensitivity for such a field. This explains the apparent anomaly that the luminance necessary to see the flash, often referred to as an 'absolute' threshold luminance, is about ten times higher than the luminance necessary to see the largest test object. But the 'absolute' threshold luminance for the whole screen, continuously illuminated, is indeed lower than the latter luminance value. It must be noted that these remarks refer only to luminance values; the actual *amounts of light* involved in the act of seeing the flash or of distinguishing the position of the test objects will be discussed in Part V.

A subject who can just detect the position of the 295′ C at a given luminance is able to detect at a still lower luminance the mere presence of the 47° (2820′) screen. Measurements (not included in Table 1) made on a few of the subjects showed that the luminance of the large empty screen at the absolute threshold—that is when its presence can just be detected by the eye—is equal to about one half of the luminance corresponding to the threshold for the 295′ C. The mean threshold for this C, according to Table 2, is $\bar{7}{\cdot}639$. Thus we may take it that for the present subjects the mean value of the absolute threshold for the empty 47° field continuously exposed is about $\bar{7}{\cdot}64 - 0{\cdot}30 = \bar{7}{\cdot}34$ (ft.-L.), which corresponds to $\bar{7}{\cdot}87$ (cd/m²). Thus the mean absolute threshold for the large field is here $0{\cdot}75 \times 10^{-6}$ cd/m². This is in agreement with the results obtained by other workers (see Denton and Pirenne, 1954a*). The absolute threshold for large fields and long exposure is known to be of the order of 10^{-6} cd/m² (Le Grand, 1948).

Test objects larger than the 295′ C, the diameter of which subtends about 25° (Fig. 2*a*), could not have been used on a 47° field without unduly cutting down the proportion of empty field which must surround the test object.

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* In this paper there is a misprint on p. 440, Summary, § 3: for '$0{\cdot}85 \times 10^{-7}$ cd m²' read '$0{\cdot}85 \times 10^{-6}$ cd/m²'. The values in the text of the paper are correct, however.

The Variation of Visual Acuity with Luminance

We consider first the mean of the results for the 22 subjects. Table 2, which provides a statistical analysis of the results in Table 1, gives for each test object the arithmetic mean of the C thresholds, and also the mean of the flash thresholds, obtained for all the subjects (using the last series of measurements made on each subject); these thresholds are given in logarithmic units as in Table 1.

TABLE 2

Statistical analysis of the results (given in Table 1) of the experiments of Part I

	Visual angle subtended by gap in C and corresponding visual acuity							$\frac{1}{5}$ sec. flash
	295′ $\frac{1}{295}$	191′ $\frac{1}{191}$	96′ $\frac{1}{96}$	24′ $\frac{1}{24}$	12′ $\frac{1}{12}$	6′ $\frac{1}{6}$	3′ $\frac{1}{3}$	
visual acuity ..	$\bar{3}$·53	$\bar{3}$·72	$\bar{2}$·02	$\bar{2}$·62	$\bar{2}$·92	$\bar{1}$·22	$\bar{1}$·52	—
meter of C (cm.) istance from eye = 4·6 cm.)	50	32	16	4	2	1	$\frac{1}{2}$	—
nber of subjects ..	16	15	21	16	21	22	21	22
an threshold	$\bar{7}$·639	$\bar{7}$·749	$\bar{6}$·046	$\bar{6}$·991	$\bar{5}$·710	$\bar{4}$·916	$\bar{3}$·559	$\bar{6}$·539
ndard deviation of resholds	0·164	0·176	0·171	0·218	0·240	0·184	0·142	0·144
rrelation coefficients of threshold with flash reshold	0·927	0·903	0·846	0·841	0·834	0·705	0·384	—
bability of numerically eater value from un-rrelated population ..	<0·001	<0·001	<0·001	<0·001	<0·001	<0·001	0·086	—

Note: As in Table 1, the threshold values given here are logarithmic values to base 10, the luminance ng expressed in foot-lamberts.

Fig. 3 (p. 10) shows these mean values of the C thresholds plotted against the corresponding acuity values. The curve joining these values covers a luminance range of about 4 log units; as we have seen (p. 8), it starts 0·3 log unit above the absolute threshold for the large empty field. The corresponding acuity range is 2 log units. It will be noted that the general trend of this curve, which is indicated by the longer of the straight broken lines, corresponds roughly to a slope 0·5, a fact which will be referred to in Part V.

In the present range of measurements the mean curve of log acuity versus log luminance is steepest at the lowest luminance values. Thus a given relative change in luminance has a larger relative influence on acuity near the absolute threshold than at higher levels. At low levels the curve has a slope in the neighbourhood of unity, the acuity being, therefore, roughly proportional to the luminance. The steepest slope is found at the lowest levels, which suggests that if the curve could be extended to lower acuity values it would become steeper still. This is in agreement with the finding that the absolute threshold of the 47° field is only 0·3 log unit below the threshold of the 295′ C. When

we measure the absolute threshold of a subject for the large field, we are in fact asking the subject to detect a large lighted gap, namely the 47° field itself, amidst the surrounding darkness. Thus it may be argued that such a visual task is not essentially dissimilar to detecting the position of the lighted gap in a black C placed on a uniformly lit background. We may therefore consider that a

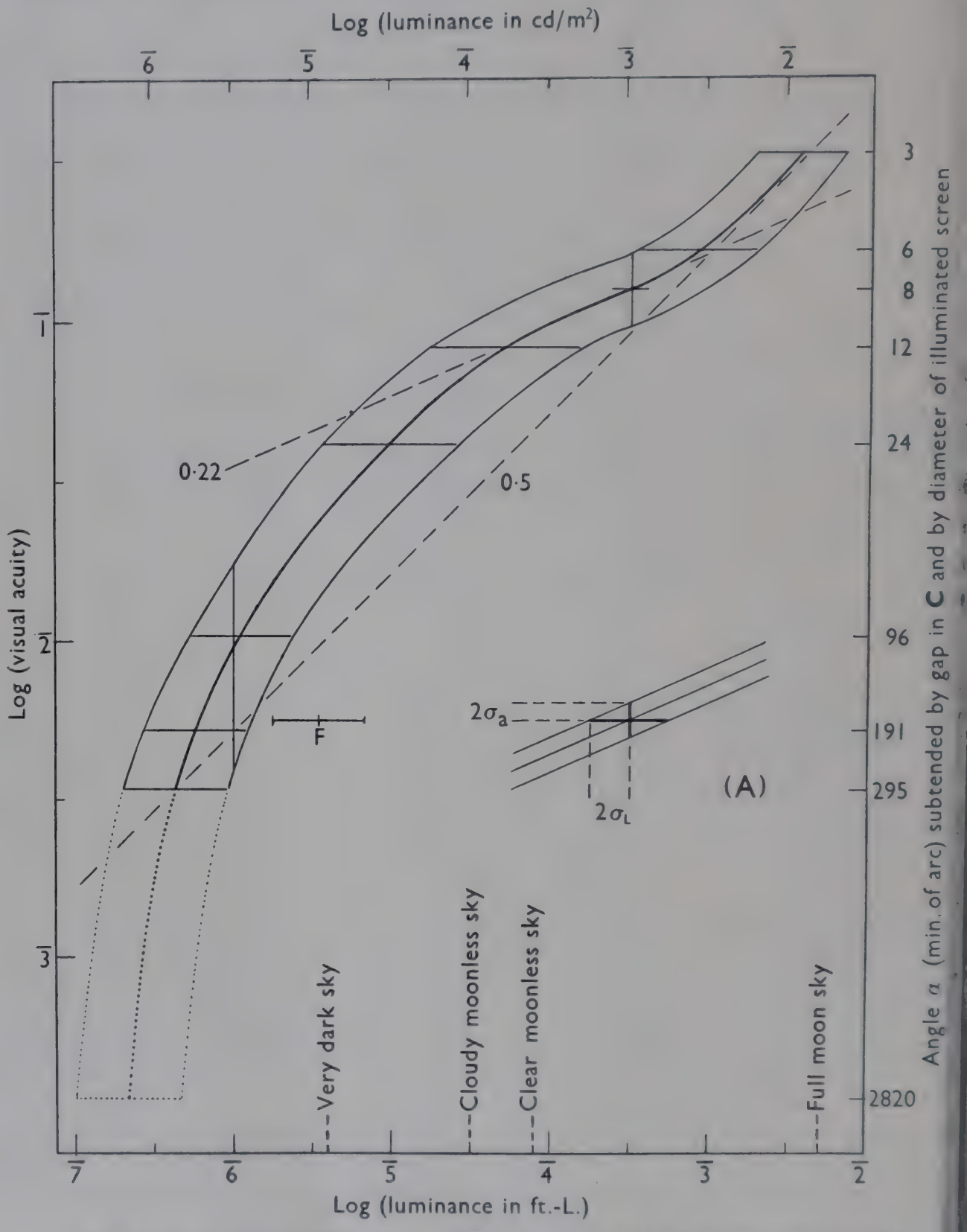

FIG. 3. Acuity versus field luminance. The main curve joins the mean experimental values of 22 subjects for the C thresholds (Table 2); the curves on either side join the values between which fall the results for the bulk of the population (as explained in the text, p. 14). The line F gives corresponding values for the flash threshold. Diagram (A) is a simplified half-scale representation, displaced downwards by an arbitrary amount, of the acuity-luminance curve near acuity $\frac{1}{8}$. The luminance values of the night sky under various conditions are plotted on the lower abscissa scale.

certain very low visual acuity value corresponds to the determination of the absolute threshold for the 47° field. This acuity value may tentatively be taken as the reciprocal of the angle 2820′, which is subtended at the eye by the diameter of the large field itself. Fig. 3 shows that a reasonable extrapolation (dotted line) of the experimental curve can in fact be made to end at the point corresponding to acuity $= \frac{1}{2820}$ and log luminance $= \bar{7}{\cdot}34$, which is the absolute threshold for the 47° field.

Similarly, the value of the mean flash threshold is also shown in Fig. 3 at F, at an acuity value corresponding to the diameter of the test field, 3° = 180′. In this case the luminance value is higher than that corresponding to the threshold of a C having a gap of similar size to that of the 3° field; however the experimental conditions are different. This question will be discussed in Part V.

Fig. 3 also shows that at higher luminances the rate of increase of acuity slows down. The slope of the curve passes through a minimum at an inflexion point corresponding to log acuity $= \bar{1}{\cdot}1$ (visual angle 8′) and log luminance $= \bar{4}{\cdot}5$. Here, over a range of luminance of the order of 1 log unit, the slope of the curve, indicated by the shorter straight broken line, is about 0·22, an increase of ten times in luminance corresponding to an increase of only 1·7 times in acuity. After this region the slope increases again, as indicated by the position of the threshold value for the 3′ C. We now reach a second region of rapid acuity increase. This region lies outside the range of the present investigations, but it has been studied by other workers, and it is of interest to compare the findings of these investigations with those of the present study where they overlap.

Comparison with other results. Fig. 4 combines the results of the present investigations with those obtained by Shlaer (1937) in a higher range of acuity, which includes the final horizontal plateau corresponding to the highest acuity values. Thus the figure shows the general variation of visual acuity, measured with a Landolt C, from the highest to the lowest luminance levels at which measurements have been made, and includes the value corresponding to the absolute threshold of the whole field. The intensity range extends over about 9 log units. The horizontal broken line at acuity $\frac{1}{3}$ indicates the upper limit of the present measurements.

In Fig. 4 the dotted line represents an extension of Shlaer's curve based on the present results. There is satisfactory agreement between the present results and those of Shlaer over the range where both series of measurements overlap. This is clearly shown in a paper by Pirenne and Denton (1952) in which the individual experimental points are plotted in Fig. 1. Shlaer's results were obtained with white light using an artificial pupil 2 mm. in diameter, whereas the present results relate to binocular vision and natural pupils. However, as will be shown in Part V, in the present investigations the variation of the pupil with luminance was of minor importance except at the highest acuity values of Fig. 3, namely $\frac{1}{6}$ and $\frac{1}{3}$; and when pupil variation is taken into account the above-mentioned agreement is rather improved.

Lythgoe's (1932) measurements start at about acuity $\frac{1}{3}$, that is, at the level where the present measurements stop. Accordingly there is no overlap between the two sets of results, so that no comparison is possible.

The scotopic acuity-luminance curve from the lowest values to acuity $\frac{1}{8}$, as determined in the present experiments (Fig. 3), bears a resemblance to the photopic part of the general curve of Fig. 4, which ranges from acuity approximately $\frac{1}{3}$ to acuity 2·5. This photopic curve is characterized by a rapid initial rise of acuity and by a final plateau. In the scotopic curve, however, there is no

horizontal plateau; the curve ends in a transition zone containing the inflexion point at acuity $\frac{1}{8}$ and leading to the steep beginning of the photopic curve. It has been shown by Shlaer, Smith and Chase (1942) that when the subject always uses the most accurate part of his retina it is likely that both rods and cones co-operate in the acuity range between about $\frac{1}{8}$ and $\frac{1}{3}$, while the rods alone are active at lower levels, and the cones alone at the highest levels.

In Fig. 4, Shlaer's results show that, except at the highest luminances, central foveal vision (indicated by the inner curve) leads to lower acuity values than

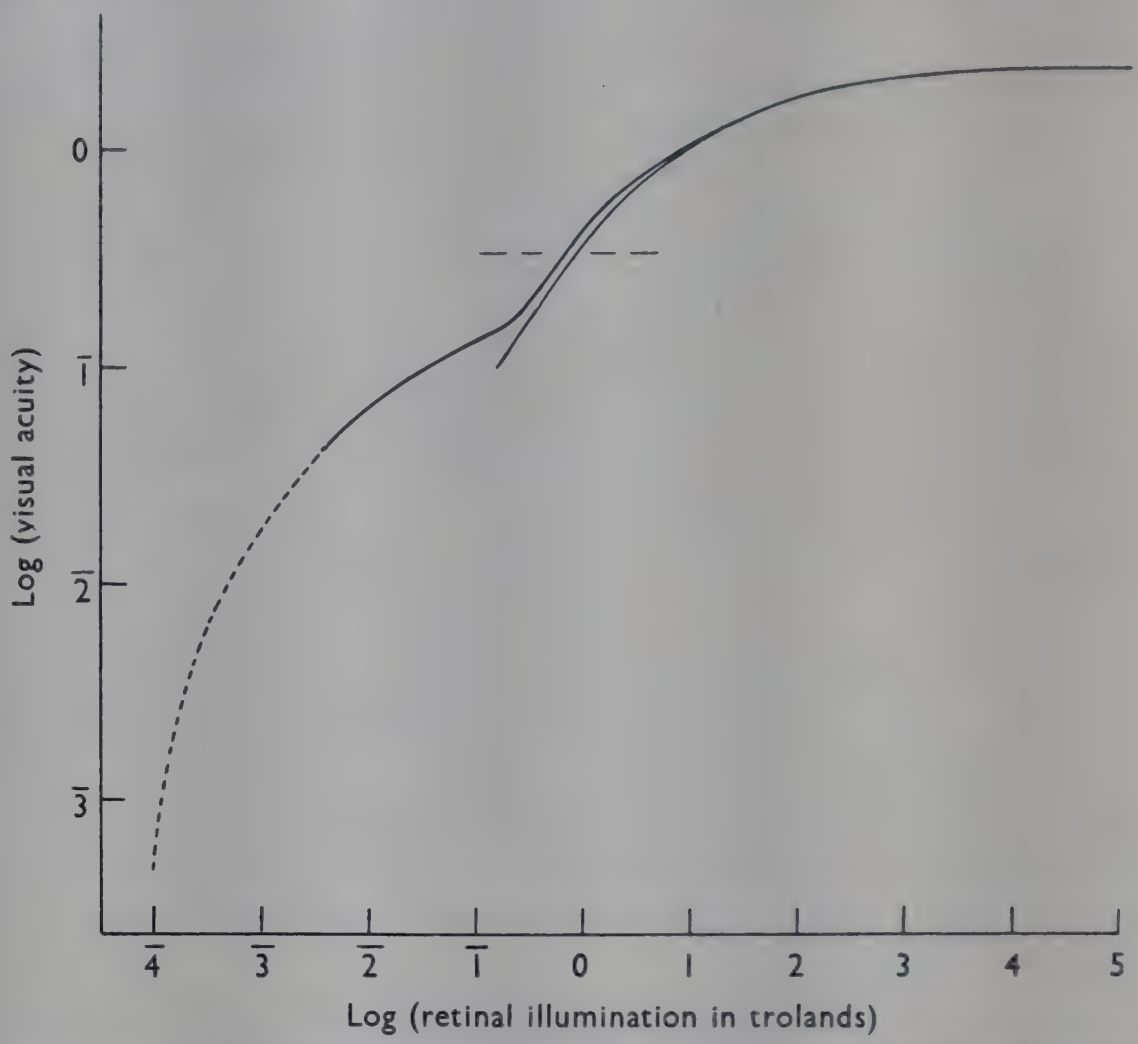

FIG. 4. Diagram showing the general variation of visual acuity with field luminance, using a Landolt C test object. The present experiments do not extend beyond an acuity value of $\frac{1}{3}$, indicated by a broken horizontal line on the figure. Scotopic acuity extends from the lowest values up to the break in the curve at about acuity $\frac{1}{8}$; there is an intermediate region between about $\frac{1}{8}$ and $\frac{1}{3}$; and photopic acuity extends from about $\frac{1}{3}$ to the final plateau value, which, in the present case, corresponds to acuity 2·5. The outer curve represents the results for Shlaer's subject A. M. C., when using the most suitable part of his retina, the dotted section representing an extension of Shlaer's results towards the lowest levels, made on the basis of the mean curve of Fig. 3. The inner curve gives the acuity of the same subject when using central vision (Shlaer, 1937).

parafoveal vision; for acuity values of the order of $\frac{1}{10}$ therefore, there will be a considerable drop in acuity if the subject does not use his eyes in the best way (cf. Part II, 'Influence of Training').

The light intensity in Fig. 4 is expressed in terms of the troland, formerly called photon; this is the 'retinal illumination' produced by a surface having a luminance of 1 cd/m² when the pupil area is 1 mm² (Walsh, 1953).

The luminance of the night sky. Some information on the brightness of the night sky is of interest in the present connexion. Direct measurements (W. S.

Stiles, private communication) of zenith sky luminance made by the National Physical Laboratory at Teddington during the Second World War gave about 5×10^{-3} ft.-L. ($1{\cdot}7 \times 10^{-2}$ cd/m^2) under full moon conditions, about 8×10^{-5} ft.-L. ($2{\cdot}7 \times 10^{-4}$ cd/m^2) on a clear moonless night and 3×10^{-5} ft.-L. ($1{\cdot}0 \times 10^{-4}$ cd/m^2) on a cloudy moonless night. With sufficiently thick cloud still lower values are possible, the lowest recorded being 4×10^{-6} ft.-L. ($1{\cdot}4 \times 10^{-5}$ cd/m^2). These luminance values are plotted on the lower abscissa scale of Fig. 3.

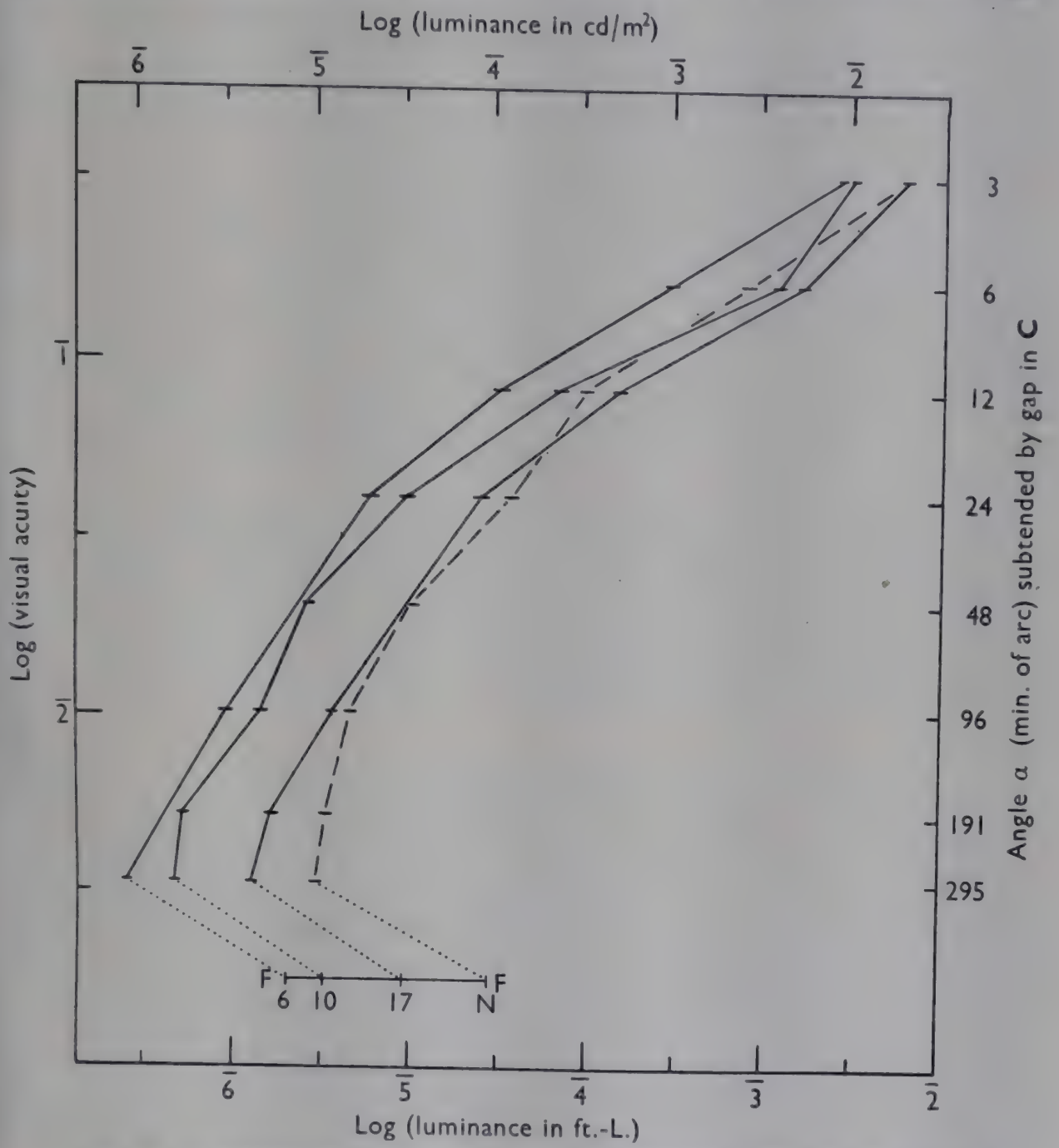

FIG. 5. The variation of acuity with luminance. Individual C threshold values of Subjects 6, 10 and 17, given in Table 1, and of an additional subject, N (broken line), given in Table 3. The points on the line FF give the respective flash thresholds.

The colour temperature of moonlight is not very different from that of daylight—5400° K. The spectral distribution of starlight is not known exactly but its colour temperature is lower than that of moonlight, probably in the neighbourhood of 3500° K. The above values of sky luminance are all greater than the absolute threshold for normal human subjects. Indeed, in these latitudes the night sky is apparently never so dark that it does not look lighter than the ground to the normal dark-adapted eye.

Individual Threshold Variations

Fig. 5 gives the variation of acuity with luminance for three of the twenty-two subjects, namely Subjects 6, 10 and 17 (it also gives similar findings for another subject, N, to be considered later). The curves are plotted from the data of Table 1; thus each individual curve represents a series of measurements obtained during a two-hour sitting, namely, the last series made with the subject (earlier sittings are regarded as training periods). The number of curves is limited to four because it is hardly possible to show clearly a larger number of curves on the graph. Of the subjects whose curves are given, Subject 6 was one of the two subjects giving the lowest flash thresholds, and Subject 17 gave the highest flash threshold (apart from Subject N). The value of the flash thresholds for the four subjects are also shown in this figure, on the line FF.

As the visual sensitivity of the experimenter was about average compared with the population of subjects, he was in a position to observe directly the effect of individual sensitivity differences. For instance, in the case of the large 295′ C test object, the experimenter was sometimes able to see clearly the gap in the C at luminance levels at which the least sensitive subjects saw it only as an unbroken ring with very vague outlines. Conversely, the more sensitive subjects were able to resolve the C at luminance levels at which the experimenter found himself in complete darkness and could see neither test object nor illuminated field.

Fig. 5 indicates that for the flash and for each C test object there is a scatter of threshold values in the population of twenty-two subjects. The standard deviation of the individual values was calculated for each kind of threshold on the basis of the measurements given in Table 1. These values of the standard deviation are given in Table 2 (p. 9); as usual they refer to the flash thresholds and the C thresholds, that is, to the logarithms of the threshold luminances.

The standard deviation of the flash threshold is 0·144 log unit. Assuming that the distribution of threshold values in our population of twenty-two subjects was approximately normal, we must therefore expect that a range of $4 \times 0{\cdot}144 = 0{\cdot}576$ log unit will contain the values for about twenty-one out of twenty-two of the population. This is in general agreement with the results of other workers who used a larger number of subjects. For instance Hecht and Mandelbaum (1939) found that the flash thresholds of 110 subjects, measured in a similar way, covered a range of about 1 log unit. In the latter investigation the subjects' ages varied from 15 to 65 years. There was a slight change in the distribution of rod threshold with age, but unfortunately the various age groups have been so arranged (15–20; 21–25 etc.) that they cannot be directly compared with our group of subjects. Sheard (1944) suggests that the normal range among subjects similar to ours is 0·5 to 0·7 log unit.

Table 2 shows that the standard deviations for the C thresholds are of the same order as the standard deviation for the flash threshold. Only one of the C thresholds, that for the 12′ C, has a standard deviation differing significantly ($P < 0{\cdot}001$) from that of the flash threshold. For this measurement the standard deviation is 1·7 times that of the flash threshold.

In Fig. 3 (p. 10) the values corresponding to twice the standard deviations are marked on either side of each mean threshold value including the flash threshold value. (The standard deviation is referred to as σ_L in diagram A.) The points representing corresponding amounts of spread at the various acuity levels

have been joined by smooth curves drawn on either side of the mean log acuity —log luminance curve. The curves have been extrapolated to the point corresponding to the absolute threshold for the 47° field.

Correlations between Flash Threshold and C *Thresholds*

Product-moment correlation coefficients have been calculated between the flash threshold and the C threshold of each C taken in turn for the twenty-two subjects. Their values are given in Table 2. Up to the 6′ C, that is up to acuity $\frac{1}{6}$, the correlation coefficients are statistically significant ($P < 0{\cdot}001$). The correlation coefficients are highly significant for these acuity values but decrease between acuity $\frac{1}{295}$ and acuity $\frac{1}{6}$. For acuity $\frac{1}{3}$ the correlation coefficient is not significant. It is clear that we are approaching an acuity range where there is less correlation with the flash threshold. This is to be expected, for the higher acuities corresponding to photopic luminances—which involve foveal, cone vision—are likely to be less closely correlated with the flash threshold—which refers to dark-adapted rod vision. At very high luminances visual acuity becomes independent of luminance, the log acuity versus log luminance curve reaching a plateau (Fig. 4); there is no longer any reason to expect a correlation between acuity and sensitivity to light once the plateau is reached, since acuity has then ceased to be dependent on luminance.

Since the flash threshold and the thresholds for the larger C's show a high degree of correlation, correlation must also exist between the various C thresholds themselves. Accordingly, at the lower acuity levels, we must expect the individual curves of log acuity versus log luminance to be similar in shape but to be shifted by various amounts along the log luminance axis. For example, this is approximately true of the curves of Fig. 5 (p. 13) up to acuity $\frac{1}{24}$, after which the curves cross over. The differences between the shapes of the curves may be due in part to errors of measurement as well as to genuine individual differences.

Distribution of the Individual Acuities at a given Luminance

If the three main curves of Fig. 3 are cut by a vertical line corresponding to a given luminance, the segments (each approximately equal to $2\sigma_a$) intercepted on the vertical line give the spread of log acuity values corresponding to the spread $2\sigma_L$ on either side of the C thresholds, as shown in diagram (A) of Fig. 3. The two extreme curves, being at either side of the mean curve at a distance equal to twice the standard deviation σ_L, must contain between themselves at any luminance value the individual curves of about twenty-one out of twenty-two of the population. The vertical segments they intercept must therefore contain the bulk of the acuity values of the population, just as the horizontal segments intercepted contain the bulk of the C thresholds. It may be pointed out that even if the C thresholds in logarithmic units were quite symmetrical in their distribution, the log acuity values at low luminance levels would have a slightly skew distribution because of the convexity of the acuity-luminance curves in the double logarithmic plot. Thus, Fig. 3 shows that at log luminance $= \bar{6}$, the spread about the middle curve (which corresponds roughly to the median acuity value) corresponding to twenty-one out of twenty-two of the population covers $+0{\cdot}26$ and $-0{\cdot}36$ log unit.

Fig. 3 also shows the variation in magnitude of the total spread of log acuity with the luminance. At low luminances, where the curve is steepest, the spread is largest. It decreases steadily with increasing luminance, reaches a minimum

at the inflexion point of the curve (log luminance = $\bar{4}$·5) and then increases again (cf. Fig. 9*a*, p. 27). It ranges from about 0·62 at log luminance = $\bar{6}$ to 0·22 at log luminance = $\bar{4}$·5. This means that at the first level the acuity in the bulk of the population varies between the relative values 1 and 4·2, while at the second brightness level the variation lies between the relative values 1 and 1·7 only. The relative individual differences in acuity are thus much larger at a very low luminance than at a luminance a little below that of a moonlit sky. This is due to the general shape of the curves, and it would remain true even if the spread of the visibility thresholds did not change at all from one level to another. From a practical point of view it must be borne in mind that the lowest luminance levels considered here are below that of a very dark night sky; they may, however, correspond to the luminance of objects on the ground.

Additional Experiments with a Subject having a High Flash Threshold

Experiments were made with a subject (a woman aged 32) who will be called Subject N, whose flash threshold was 0·9 log unit above the mean value of the group of young subjects discussed above. The flash threshold of Subject N was found to vary in the course of one single day; on one occasion, for instance, it was found to be 0·4 log unit lower at 8 a.m., before breakfast, than at 10 a.m., after breakfast. It seemed that the threshold tended to be higher during the day than early in the morning or late in the evening. Except for the high value of the final threshold, the course of dark-adaptation of this subject measured under standard conditions (cf. Fig. 1A, p. 57) presented no anomaly. Since the age of Subject N was outside the range for the group of twenty-two subjects, the results of the measurements were not included with those of this group but they will be briefly described here.

The values for the flash and C thresholds of Subject N, measured in day time, are given in Table 3. They are also plotted in Fig. 5. The 295′ C and 191′

TABLE 3

Results of additional experiments with a subject, N, having a high flash threshold ($\bar{5}$·45); *measurement of* C *thresholds*

	Visual acuity							
	$\frac{1}{295}$	$\frac{1}{191}$	$\frac{1}{96}$	$\frac{1}{48}$	$\frac{1}{24}$	$\frac{1}{12}$	$\frac{1}{6}$	$\frac{1}{3}$
C threshold	$\bar{6}$·46	$\bar{6}$·52	$\bar{6}$·66	$\bar{6}$·98	$\bar{5}$·57	$\bar{5}$·98	$\bar{4}$·89	$\bar{3}$·77

Note: As in Tables 1 and 2, the threshold values given here are logarithmic values to base 10, the luminance being expressed in foot-lamberts.

C thresholds were 0·8 log units higher than the mean for Subjects 1 to 22, a result which is quite consistent with the high flash threshold. The deviation from the mean results, however, decreased steadily with increasing acuity, and at acuity $\frac{1}{6}$ the threshold was the same as the mean threshold of the other subjects.

The correlations of Table 2 were recalculated to include Subject N with the twenty-two other subjects, giving the values shown in Table 4. It was found that the general trend of the correlations was the same as in Table 2 except that the correlation for acuity $\frac{1}{6}$ was no longer significant while that for $\frac{1}{3}$ was now significant ($P < 0{\cdot}05$). Thus if a subject such as N had been present in the group of younger subjects of Table 1 this would not have led to any great change in the conclusions that were reached regarding this group.

TABLE 4

Correlations of mean flash threshold with mean C thresholds when the measurements of Subject N are added to those of Subjects 1 to 22

	Visual acuity						
	$\frac{1}{295}$	$\frac{1}{191}$	$\frac{1}{90}$	$\frac{1}{24}$	$\frac{1}{12}$	$\frac{1}{6}$	$\frac{1}{3}$
Correlation coefficients of flash threshold with C thresholds ..	0·972	0·951	0·892	0·859	0·674	0·395	0·465

Including Subject N in this group led to a slight increase in the mean threshold for the larger C test objects, and consequently in the mean absolute threshold of the 47° field, $\bar{7}$·87, which became $\bar{7}$·93 log units (luminance in cd/m^2). This value, 0·85 $\times$ 10^{-6} cd/m^2, was used in a discussion of the absolute sensitivity and functional stability of the human eye (Denton and Pirenne, 1954a). It may be pointed out here that the apparent skewness of the distribution of the individual flash threshold values mentioned earlier in this paper is not statistically significant, particularly when Subject N is not included with the others.

Assuming that the retina functions according to the general scheme put forward by Pirenne and Denton (1952), the acuity measurements relating to Subject N might be explained by a loss of the power of spatial summation affecting only the larger functional units of this subject's retina, the summating properties of the smaller units and the sensitivity of the individual rods being little affected. This would explain the fact that the threshold was raised for the large C's and for the 3° flash, while its value was near average for the small C test objects. Temporary recovery of the nervous summating properties of the larger units occurring at certain times would also explain the variations in the flash threshold observed during the course of one day.

II. Visual Acuity and the Absolute Threshold: Second Series of Experiments

AIMS

Further experiments on visual acuity and flash threshold were made to study two particular points:

(a) the accuracy of the flash threshold and of the threshold of an 8′ C. The latter threshold corresponds to the acuity value, $\frac{1}{8}$, of the inflexion point in the curve of Fig. 3 (p. 10). It is a characteristic point at the end of the scotopic range of visual acuity, and it was chosen for this reason.

(b) the correlation between these two different thresholds.

In the experiments of Part I it was found that the flash threshold was correlated with the larger C thresholds up to the 6′ C, but that the correlation with the 3′ C was not quite significant ($0{\cdot}05 < P < 0{\cdot}1$). As will be shown presently, in the second series of experiments the flash threshold and the 8′ C threshold were found to be significantly correlated, thus supporting the results of the first series. In the second series, conditions such as the timing of the exposure of the test objects were controlled as accurately as possible, and the measurements were conducted in a more systematic manner than in the first series.

SUBJECTS

The experiments were made using 22 new subjects, 18 women and 4 men (Table 5). They were all university students except Subject 44 who was a soldier. Their ages varied from 18 to 22 years except for Subject 42, a coloured West African student, who was 29. The visual acuity in daylight was 0·9 for 3 subjects and higher than 1 for all the others.

The experiments were repeated at several sittings. All subjects came to three different sittings and 18 came to a fourth sitting.

METHOD AND RESULTS

The Flash Threshold

In these experiments the flash threshold was measured binocularly instead of uniocularly, no eyepiece being used; otherwise the conditions were the same as those described in Part I. Apart from a rapid preliminary measurement made either on the same or on another day, only one determination of the flash threshold was made for each subject, at one of the three or four sittings. The method employed was that developed by Hartline and McDonald (Appendix C)—a similar method had been used independently by Stiles and Crawford (1934). It consisted, essentially, of a specified number of exposures at various fixed luminances covering the entire range of uncertain seeing. Flashes of different luminances, including some which were never seen and some which were always seen, were presented in random order, mixed with 'blanks'. The luminance steps were equal to 0·1 log unit and two to four flashes were presented at each luminance level. The calculations include a suitable correction to take into account the number of 'blanks' to which the subject might have answered 'seen'. (The calculations are explained below (p. 20) for the similar case of the 8′ C thresholds.) They give a 'mean threshold' value so defined that the same number of flashes are seen below the mean value as are not seen above it on the logarithmic scale; this corresponds approximately to the log luminance at which the subject would see 50 per cent of the flashes.

The preliminary measurements were taken partly in order to learn something about the reliability of rapid measurements of the flash threshold made on untrained subjects for the first time, and partly in order to give some training to the subjects.

The results are given in Table 5 under the heading 'Flash threshold scores'. These scores do not give the actual threshold values; they represent lengths

TABLE 5

Results of experiments of Part II: measurements of flash and 8′ C *thresholds in a further* 22 *subjects*

Subject no.	Age (yrs.)	Sex	Flash threshold scores† Final (*F*)	(Prelim.)	8′ C threshold *U* scores† Sitting I	Sitting II	Sitting III	Sitting IV
23*	20	F.	12·0	(13·0)	14·0	11·3	8·0	14·3
24*	20	F.	13·7	(12·5)	11·3	11·3	9·3	9·3
25	21	M.	11·5	(14·0)	18·0	14·7	19·0	15·0
26*	20	M.	12·0	(11·5)	8·0	6·7	6·7	8·0
27	21	F.	13·0	(13·2)	11·3	10·3	13·7	11·3
28*	19	F.	10·5	(11·0)	14·0	11·0	12·7	7·7
29*	22	F.	11·0	(13·5)	12·3	9·0	6·7	9·3
30	19	F.	10·0	(10·5)	12·7	6·3	10·7	5·3
31	19	F.	9·5	(8·5)	7·0	9·0	7·7	5·3
32	20	F.	10·7	(13·0)	12·0	7·3	3·7	6·3
33	19	F.	11·7	(10·7)	12·3	10·0	10·7	13·3
34	19	F.	11·5	(11·8)	9·0	9·0	9·0	13·3
35*	22	F.	11·3	(12·2)	11·0	16·3	10·0	14·0
36	20	F.	9·5	(9·5)	5·7	12·7	5·0	5·3
37*	20	F.	10·0	(10·0)	3·0	2·7	3·7	8·0
38*	19	F.	11·0	(8·0)	8·7	9·0	5·7	7·7
39*	19	F.	11·5	(11·5)	8·7	11·7	9·3	9·3
40	20	F.	10·0	(10·5)	17·0	6·7	9·0	9·3
41	19	F.	14·5	(13·5)	12·3	11·3	8·3	
42	29	M.	10·5	(10·5)	12·3	6·0	10·3	
43	18	F.	9·0	(9·0)	12·0	6·7	6·7	
44*	21	M.	13·0	(14·5)	15·7	12·3	14·0	
Mean Scores	18 subjects		11·13	11·38	10·89	9·72	8·92	9·56
	22 subjects		11·25	11·47	11·29	9·60	9·09	

* Subjects with spectacles.

† The relationship between the scores and the actual threshold values is explained in the text.

measured on one of the neutral wedges from a fixed position and expressed in centimetres, 1 cm. corresponding very nearly to 0·10 log unit. The actual values of the 'flash threshold' can be obtained at once by adding $\bar{7}\cdot31$ to the score divided by 10; thus for Subject 23 the final score is 12·0 and the flash threshold is equal to $(12\cdot0)/10 + \bar{7}\cdot31 = \bar{6}\cdot51$ (log units, ft.-L.).

The Threshold of the 8′ C

The general conditions for measuring the 8′ C threshold were similar to those of Part I. Only one C threshold was determined at each sitting instead of several as in Part I, but the testing method was standardized and all experimental factors were brought under strict control, notably the duration of presentation of the test object, which in the previous investigation was rather indefinite.

The circular field 47° in diameter remained continuously illuminated. Between presentations, the test object, placed at the centre of the field, was hidden behind a piece of transparent plastic which had been rubbed with sandpaper, so that the luminance was little affected but the test object was obscured. This piece of plastic was moved aside to present the test object in each new position. At each sitting the test object was exposed in this way for durations of 15 seconds, separated by intervals of rest of 45 seconds, at each of a series of luminances decreasing by steps of $\Delta (\log L) = 0{\cdot}1$ over a range of 2·2 log units, the lowest luminance (ft.-L.) being $\log L_L = \bar{5}{\cdot}47$. The test therefore lasted 22 minutes. The four possible positions of the test object were presented at random. 'Forced guessing' was not used, but the subject was encouraged to give an answer when he or she had the faintest impression of the position of the C. The subject was told each time whether the answer he had given was right or wrong. All the subjects were dark-adapted for about half an hour before the measurements were started.

The different luminances were presented in this regularly decreasing sequence in order to ensure complete adaptation of the subject to each brightness level. This method also had the advantage that the subjects became acquainted with the test under conditions in which it was easy to give right answers. Thus they had an opportunity of getting trained during the test itself.

With regard to the subjects' adaptation to the luminance of the screen, the following experiment was tried in a few cases. Towards the end of a series the initial luminance was presented again, and immediately afterwards the measurements were repeated at the lower luminances. No deterioration of the subject's performance was observed. *A fortiori*, it is safe to assume that in the normal course of measurements the subjects had time to get adapted to the decreasing luminance.

For the 8′ C threshold, the Hartline-McDonald method was not followed exactly for the presentation of the various luminances, since these were not randomized; but the method was found very convenient for calculating the scores. The subjects gave correct answers, or wrong answers, or answered "don't know"; the Hartline-McDonald method takes into account the probability of the subject guessing right when he does not see the test object. The score U (Table 5) is the total number not seen, corrected for guessing (see Appendix C, p. 77). The correction for guessing is valid even if the subject tends to report a preferred position of the C when he is guessing; its validity rests on the fact that the presentations, not the responses, are random. The mean C threshold, $\log L_m$, can then be calculated using equation (21) of Appendix C, in which $n = 1$

$$\log L^*_m = \frac{U}{n} \times \Delta (\log L) + \log L_L - \tfrac{1}{2} \Delta (\log L) = U \times 0{\cdot}1 + \bar{5}{\cdot}42 \qquad (2)$$

Table 5 gives the scores U for the various sittings, I, II, III and IV, made by each subject and also the mean values for each sitting. For example, the mean score $\bar{U}$ for 22 subjects at Sitting III was 9·09, so that the mean 8′ C threshold here was $\log L_m = 0{\cdot}91 + \bar{5}{\cdot}42 = \bar{4}{\cdot}33$ (ft.-L.). The corresponding C threshold can be read off Fig. 3 (p. 10) for log acuity $= \bar{1}{\cdot}10$; it is $\bar{4}{\cdot}45$. Considering that different subjects and a different scoring method were used the results are in satisfactory agreement. The 'mean threshold' $\log L_m$ defined here corresponds approximately to a 50 per cent frequency of seeing, while in Part I the results corresponded roughly to a 75 per cent frequency of seeing.

* In equation (21) the luminance is termed I instead of L.

Accuracy of the Flash Threshold and of the 8′ C Threshold

A mean frequency-of-seeing curve for the flash threshold was derived from the results for all the subjects as follows: the individual curves giving the frequency of seeing of each subject were displaced along the log luminance scale in such a way as to make the individual mean threshold values coincide on the

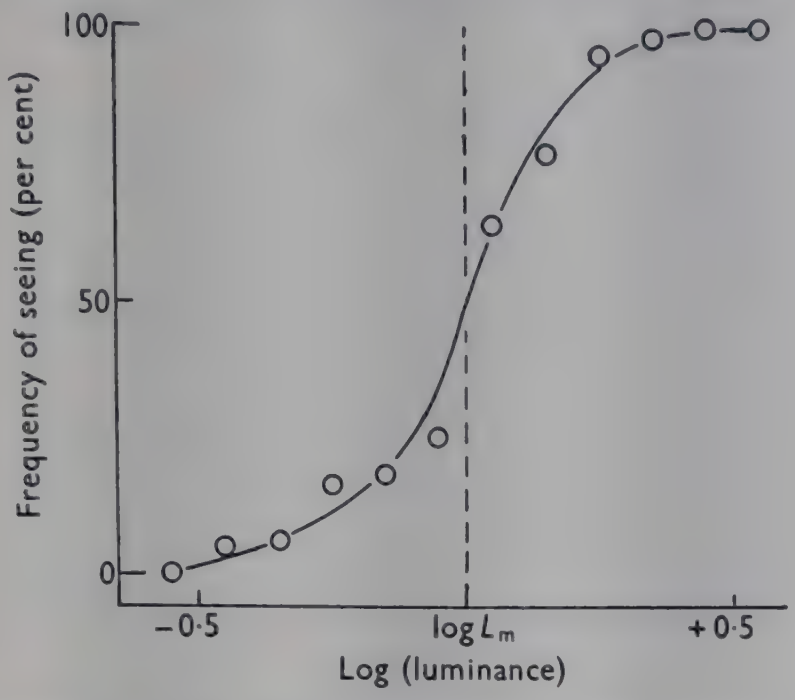

FIG. 6. Binocular flash threshold measurements. Mean frequency-of-seeing curve for 22 subjects, obtained as explained in the text. The mean threshold luminance L_m has been taken as unity, so that $\log L_m = 0$.

scale; then the frequencies of seeing were averaged for the various luminance steps above and below this value. The resulting curve (Fig. 6) is almost exactly the same as the curve obtained in a similar way by Hartline and McDonald (Fig. 2C, section A, p. 74). The uncertainty range, between almost 0 per cent and almost 100 per cent seeing, covers about 1 log unit.

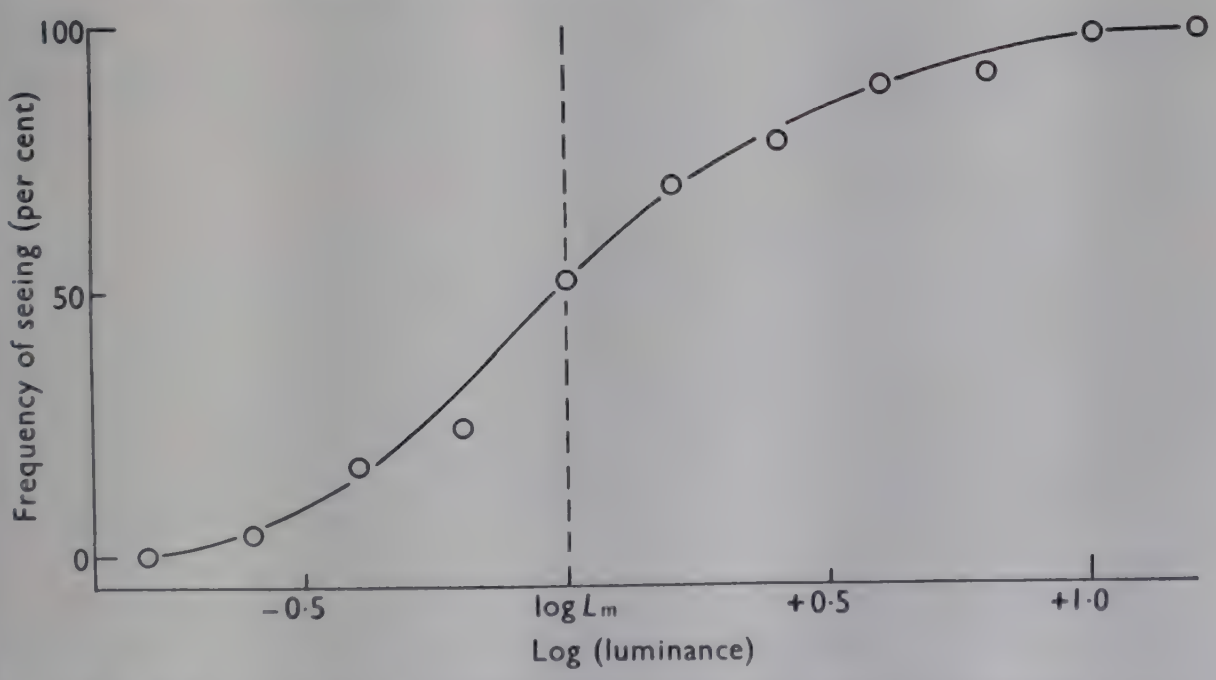

FIG. 7. Binocular 8′ C threshold measurements. Mean frequency-of-seeing curve for 18 subjects, obtained as explained in the text (p. 22). The mean threshold luminance L_m has been taken as unity, so that $\log L_m = 0$.

A similar curve (Fig. 7) was obtained for the threshold of the 8′ C. This curve is much shallower than the flash threshold curve, the uncertainty range here covering 2 instead of 1 log unit. It is shallower than the shallowest curve obtained by Hartline and McDonald, for a 3° T of low contrast (Fig. 2C, section E, p. 74). It will be noted from Table 5 that the range of uncertainty of seeing the 8′ C for one subject is actually greater than the range of the mean 8′ C thresholds for the whole group of subjects. This is also true for the flash threshold measurements.

The shape of the curves of Figs. 6 and 7 bears a direct relation to the accuracy of the mean threshold value obtained by any particular method. It is clear that, all other things being equal, the accuracy will be lower when the uncertainty range is wider. The accuracy of the 8′ C threshold, under the conditions used here, corresponds to a standard error of 0·224 log unit for an individual measurement. In the case of the flash threshold, with one flash at each 0·1 log unit luminance step, for instance, it is 0·098 log unit (Equation (25), p. 78; Table 1C, p. 79). The accuracy of the 8′ C threshold measurements is thus seen to be, comparatively, very low, particularly when it is borne in mind that the time required for one trial is markedly longer here than that required for the flash threshold. For this reason, assuming that a high degree of correlation exists between the flash threshold and the 8′ C threshold, we may expect that this correlation may sometimes fail to reveal itself purely, on account of experimental errors.

Correlation between the Flash Threshold and the 8′ C *Threshold*

Product-moment correlation coefficients (Table 6) were calculated on the basis of the experimental results. The correlation coefficient is significant ($P < 0{\cdot}05$) between the flash threshold and the *mean* of the second and third C measurements for the whole group of 22 subjects. Yet the flash threshold does not correlate significantly with the second or the third C measurement taken separately. This is in keeping with the remarks made at the end of the preceding paragraph. The influence of experimental errors is lessened when the mean of several measurements is taken, and this explains the existence of a significant correlation with the mean but not with the individual values.

Considering the 18 subjects who came for 4 sittings, we see that the flash threshold correlates significantly ($P < 0{\cdot}05$) with the mean of the second, third and fourth C measurements. The correlation is also significant ($P < 0{\cdot}05$) with the fourth C measurement taken alone, in which training must be expected to be almost complete.

In conclusion, a significant correlation is found to exist between the flash threshold and the C threshold corresponding to acuity $\frac{1}{8}$, that is, the value at which the curve of Fig. 3 shows an inflexion. This confirms the findings of the first series of experiments, in which correlation was found to exist from acuity $\frac{1}{295}$ to acuity $\frac{1}{6}$; for if correlation exists for acuity $\frac{1}{8}$, *a fortiori* it is most likely to exist for lower acuity values corresponding to luminance values nearer that of the absolute threshold. The 8′ C threshold corresponds to a luminance value equal to about 1000 times that of the absolute threshold of the continuously exposed large field.

It will be noted that the present series of measurements was carried out in a systematic, standardized manner which must have greatly reduced the possibility of the experimenter influencing the subject's response. The experimenter could know but little of the meaning of the results until the measurements were completed and the calculations carried out.

TABLE 6

Product-moment correlation coefficients calculated from the results (given in Table 5) of the second series of flash and C threshold experiments

(*a*) *Correlation coefficients between flash threshold (F) and measurements of the C threshold at successive sittings* (I, II, III, IV)

F–I	*F*–II	*F*–III	*F*–IV	
0·224	0·312	0·344	0·557*	(18 subjects)
0·246	0·416	0·337	—	(22 subjects)

(*b*) *Correlations between the flash threshold and the mean of the C thresholds, excluding the first C threshold*

$F-(II+III+IV)/3$		$F-(II+III)/2$	
0·485*	(18 subjects)	0·430*	(22 subjects)

(*c*) *Correlations between C thresholds, excluding the first C threshold*

II–III	II–IV	III–IV	
0·528*	0·511*	0·544*	(18 subjects)
0·516*	—	—	(22 subjects)

* Significant at 5%.

(*d*) *Values of the correlation coefficient necessary for significance*

Level of significance *P*	Correlation coefficients 18 subjects	22 subjects
0·1	0·400	0·360
0·05	0·468	0·423
0·01	0·590	0·537

The Effect of Experimental Errors on Correlations

If two quantities X and Y have a correlation ρ in a certain population, and measurements x and y are made of these quantities, then if x and y are subject to experimental error, the correlation between them will be less than ρ. For while cov xy = cov XY, var x and var y exceed var X and var Y by quantities equal to their error variances. If repeat measurements of x and y are available, the error variances can be assessed and allowance made for this source of bias in the estimate of ρ.

In the experiments of Part II, the large spread of the distribution of correct responses in the measurement of the 8′ C threshold produced low sample correlations. The correlation between flash threshold and the fourth C threshold was 0·557. The error components of variance were estimated from the differences between the third and fourth C thresholds and from the differences between the

flash threshold and the preliminary measurements of the flash threshold. The variances were:

	Flash threshold	*Fourth C threshold*
Variance	1·30	10·58
Error component	0·36	5·02
Difference ('specific variance')	0·94	5·56

The correlation may now be adjusted by replacing the variances in the denominator by the 'specific variances', that is the variances due to variation between subjects only, with the error component removed. Thus the estimate of ρ becomes

$$0{\cdot}557 \times \sqrt{\frac{1{\cdot}30 \times 10{\cdot}58}{0{\cdot}94 \times 5{\cdot}56}} = 0{\cdot}90.$$

If the flash threshold is assumed to be equally correlated with the second, third and fourth C thresholds a more precise estimate of the correlation can be made using all three measurements. A similar calculation gives the estimate $\rho = 0{\cdot}65$. The difference between the two values may be due to chance variations, but is more probably due to a training effect which makes the value of ρ higher for the later measurements of the C threshold.

It should be mentioned here that if the 'filter factor' theory (discussed below, p. 27) held strictly, these adjusted correlations should be unity. The high values actually obtained confirm that the theory provides a good approximation even at the fairly high luminances used in the C threshold experiments of Part II.

If y is subject to much greater experimental error than x, the correlation between x and Y may be greater than that between y and Y, so that x provides a better estimate of Y than does y. Without loss of generality it may be assumed that X and Y have unit variance and the error components of variance of x and y are σ^2 and σ'^2.

Then

$$r_{yY} = \frac{1}{\sqrt{1+\sigma'^2}}, \qquad r_{xY} = \frac{\rho}{\sqrt{1+\sigma^2}}$$

$$r_{y_1y_2} = \frac{1}{1+\sigma'^2}, \qquad r_{xy} = \frac{\rho}{\sqrt{(1+\sigma^2)(1+\sigma'^2)}} \tag{3}$$

Thus $r_{xY} > r_{yY}$ if $r_{xy} > r_{y_1y_2}$. If the correlation between x and y is as high as that between repeat measurements of y, x provides as good an estimate of Y as does y.

In the experiments of Part II, as may be seen from Table 6, the correlations between repeat C threshold measurements are little higher than the correlations between these measurements and the flash threshold. Accordingly, even if it is required to estimate the luminance needed for exactly this acuity, the flash threshold provides nearly as good a measurement as the C threshold. The flash threshold would therefore probably be preferred, in view of its greater ease of measurement.

The Influence of Training

From the present experiments, as well as those of Part I, the general conclusion emerged that the influence of training is very small in the case of the flash threshold. Some further experiments confirmed this, while showing that training can have a marked influence when the absolute threshold is measured using a

continuously exposed 3° field without fixation. In the case of the flash threshold it seems that the main point is to make sure, using a few preliminary trials, that the subject thoroughly understands the nature of his task. Then, provided the subject is attentive and trying to do his best, there is no significant change in the results on repeating the measurement several times at one sitting.

In the case of the C threshold, the subject's task is much more complicated, and there are indications that training exerts an influence on the results, at least in certain cases. For instance, the threshold of Subject 40 dropped by 1 log unit between the first and second sittings (Table 5, p. 19). This subject said that she had not discovered the advantages of parafoveal vision before the second sitting, although they had been pointed out to her before the first sitting. Fig. 4 (p. 12) shows that the value of a subject's acuity may drop markedly when he

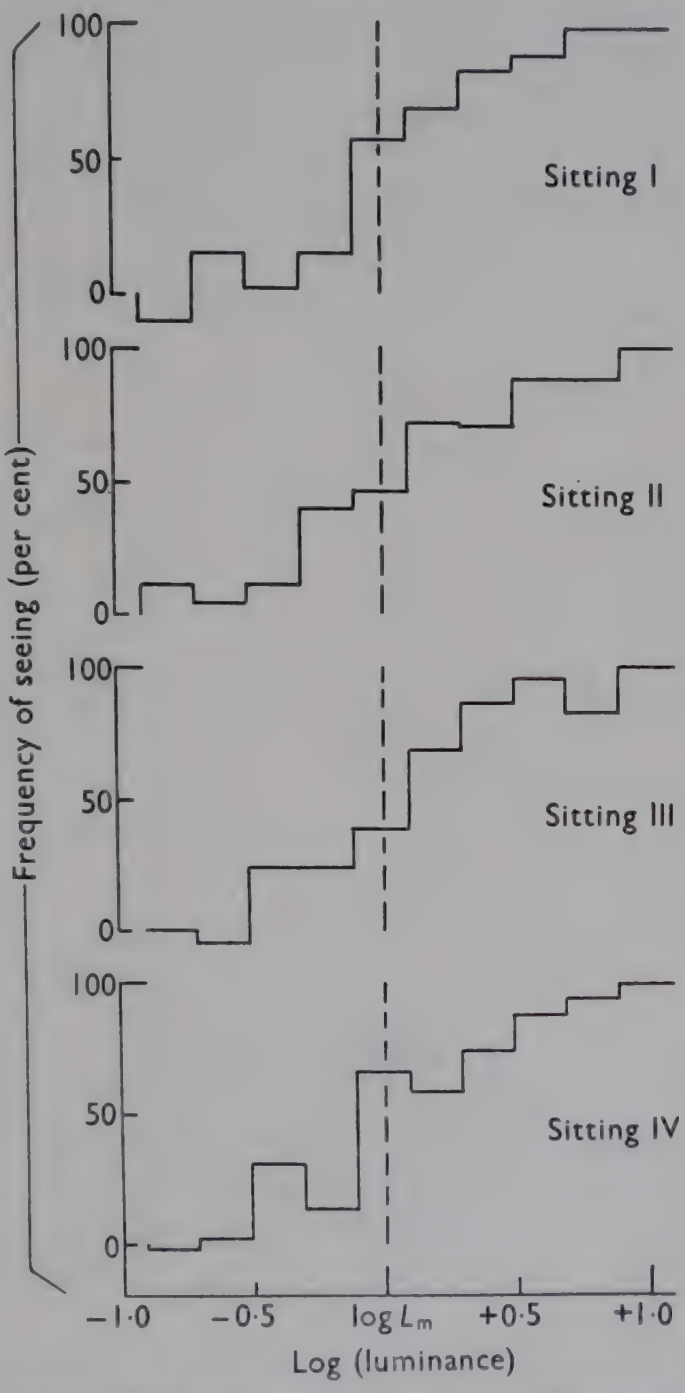

FIG. 8. Diagram to illustrate the absence of training effect in the four sets of 8′ C threshold measurements. The values shown are in each case the mean for 18 subjects. (Fig. 7, p. 21, represents the average of these measurements.) The occasional negative values arise from the correction for guessing. The mean threshold luminance L_m has been taken as unity, so that $\log L_m = 0$.

purposely uses central instead of parafoveal vision. This fact is related to the preceding remarks and, more generally, to the difficulty of making acuity experiments at these levels, where there is 'rivalry' between the fovea and the parafovea, in comparison with flash threshold measurements made using a point of fixation.

In the present experiments it seems that training became practically complete after the first sitting. But there is every reason to believe that if the instructions had been inadequate, or if the subjects had been careless over the experiments, some of them at least would have given results quite different from those which were reported.

Fig. 8 shows that there is no general effect of training on the scatter of the present measurements. The block diagrams give the mean frequency of seeing, corrected for guessing, for the four sittings; these are the diagrams which, combined, gave the curve of Fig. 7. There is little obvious difference between the various sittings.

III. The Filter Factor Theory

With a view to explaining the individual variations in acuity in the population, and at the same time the general similarity in shape of the log-acuity/log-luminance curves, we may examine the following simple hypothesis, which will be called the 'filter factor' hypothesis. The phrase 'filter factor' is used by analogy with the photographic filter factor, which relates to the lengthening of exposure necessary when a given colour filter is used with a camera; thus our 'filter factor' is quite different from the psychological 'factors' which may be revealed by factor analysis. The 'filter factor' hypothesis in its simplest form assumes that a subject, A, behaves as if he had the same eyes, brain, mind, etc. as a subject, B, but had in front of these eyes light filters of transmission $1/k$, the value k being the filter factor. According to this hypothesis A would always need k times more *external* light than B to perform any given visual task. If this hypothesis is applied to the experimental tasks of Part I, we find that in the logarithmic plot of Fig. 5 (p. 13) A's and B's curves would be of the same shape, but A's curve in relation to B's would be shifted horizontally as a whole towards higher luminances by an amount equal to log k, i.e. to the optical density which has been defined by equation (1) (p. 2). This horizontal shift is illustrated in Fig. 9*a*, which gives curves for both A and B similar to those of Fig. 5. In

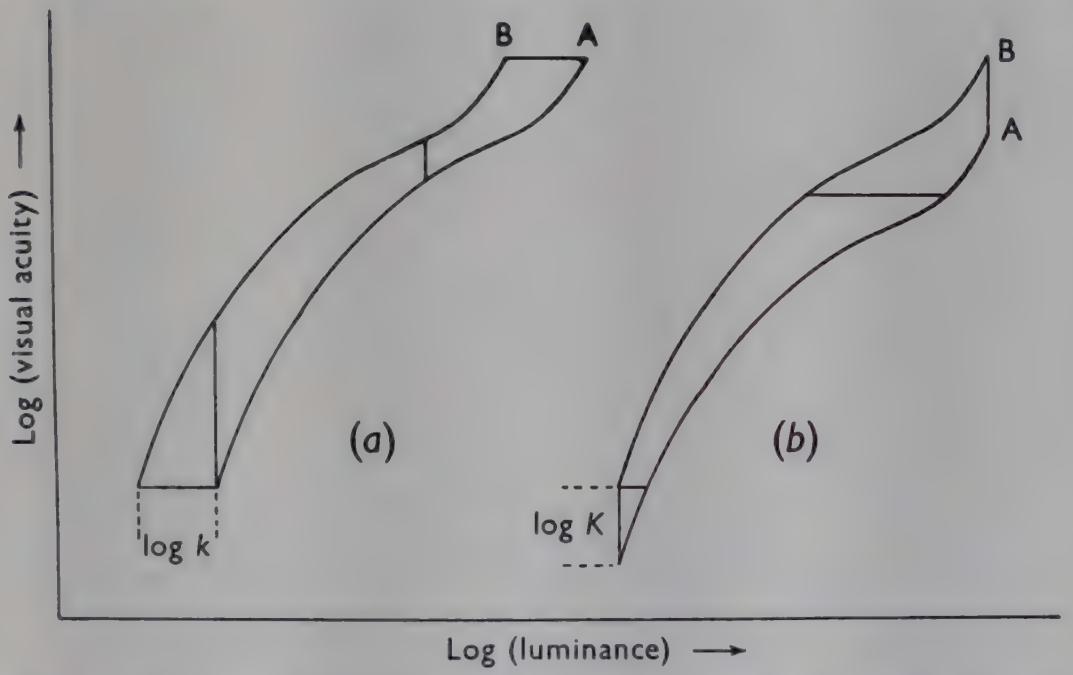

FIG. 9. Diagram to illustrate (*a*) the Filter Factor theory, (*b*) an alternative hypothesis.

(*a*) The Filter Factor theory. Subject A has the same acuity as Subject B provided the luminance is multiplied by a constant factor k at all levels. The vertical lines indicate the variations of acuity at two fixed luminance levels.

(*b*) An alternative hypothesis. The acuity of Subject B would be K times that of Subject A at all luminance levels. The horizontal lines show the variation in the C threshold which would then exist at two fixed acuity levels.

such a case, the curves representing the variation of log acuity with log luminance would be the same in all subjects, but they would be displaced along the log luminance axis by various amounts corresponding to the relevant values of the logarithm of k, the filter factor of the subject.

It will be noted that the filter factor k here applies to changes in light intensity, whereas the photographic 'filter factor' or 'exposure factor' applies to changes

in exposure times. The 'Ilford Colour Filters' handbook (1953) states: "Since a colour filter functions by absorbing a part of the light which falls upon it, it follows that when a filter is in use on the camera lens, the exposure required will be greater than if it were made without the filter. The ratio of the filtered exposure to the corresponding unfiltered exposure is known as the 'exposure factor' or 'filter factor'." The term 'exposure factor' is probably to be preferred in the case of photography; in the present Report 'filter factor' will be used with the meaning defined above.

The filter factor hypothesis may be illustrated by imagining Subject B in a room at night watching the outside surroundings through a clear window. It is assumed that there is no artificial lighting in the room or outside, and that the outside illumination does not vary. Suppose now that the window is replaced by a sheet of spectrally neutral light-absorbing glass transmitting only $1/k$ of the light transmitted by the clear window, but otherwise of the same quality as the original glass. According to the theory in its most simple and extreme form, the visual performance of Subject B would then become the same as that of Subject A looking through the clear window.

If we now increase the outside illumination by a factor k, the visual performance of Subject B looking through the darker window of transmission $1/k$ will be just the same as when looking through the clear window with the original illumination. The only difference between the two human subjects therefore would be that one of them, A, would always require k times more external illumination than the other, B, in order to have the same visual acuity. The hypothesis as a first approximation assumes that A and B are identical except that A always sees, as it were, through a transparent screen of transmission $1/k$. Experiments on perceptual efficiency to be described in Part IV will illustrate this theory further.

The curves of Fig. 5 (p. 13) suggest that the filter factor theory is approximately true from the lowest acuity levels up to about acuity $\frac{1}{8}$. The correlations found in both Part I and Part II give firm support to this suggestion. The uncorrected correlations found in Part II (p. 23) are rather low but this is largely due to the high variability of measurements of the 8′ C threshold. At the corresponding luminances the acuity is highest in a parafoveal region close to the fovea and this probably makes the visual task especially difficult. The influence of slight eye displacements must be particularly large here (cf. Fig. 4, p. 12) and, on account of the fixation reflex, the subject may be continually tempted to use pure foveal vision. All the subjects said that the measurements with the smaller test objects used in Part I entailed the greater amount of strain and fatigue. However, as discussed in Part II (p. 24), when allowance is made for the large experimental error, the correlations reach fairly high values. The experiments are thus in good agreement with the filter factor hypothesis, in spite of these complications.

Thus the filter factor hypothesis explains the present results in the range corresponding to rod vision. It becomes of doubtful value when the cones begin to come into play (at acuity $\frac{1}{8}$ or thereabouts), and it is possible that it does not apply at higher levels where pure cone vision is being used. It evidently loses its meaning at the highest acuity and luminance values, where acuity has become constant and independent of the luminance level (cf. Fig. 4). In the latter connexion, it is unnecessary to point out that there is a certain critical luminance level above which the subject will not 'see' any more in the percept with further increases in luminance—and may even see less if the luminance

becomes very high. Below the critical level, however, differences in luminance certainly affect the percept, as, for instance, in the case of a watchmaker studying an intricate piece of mechanism.

Confining our attention to pure rod levels, we might consider the following alternative hypothesis to the filter factor hypothesis: a given subject, B, has an acuity equal to K times that of another subject, A, at any given luminance, K being a constant. Thus, in the double logarithmic plot B's curve would be the same as A's except for a translation *upwards* by an amount log K. This upward shift is illustrated in Fig. 9*b*. In such a case all the individual curves would be of the same shape, but they would now be displaced by various shifts along the *vertical*, acuity, axis. This hypothesis must be rejected because the observed distribution of acuities at the various luminance levels discussed in Part I (Fig. 3, p. 10) is completely at variance with the type of distribution predicted in Fig. 9*b*.

The filter factor theory therefore remains as the best explanation of the results. A low filter factor has been suggested as an explanation of the fact that owls see better than men on a dark night (Hecht and Pirenne, 1940). This has received support from the experiments of Dice (1945), who found that certain species of owls were able to see objects under an illumination of between one-hundredth and one-tenth of the light intensity that man requires for vision.

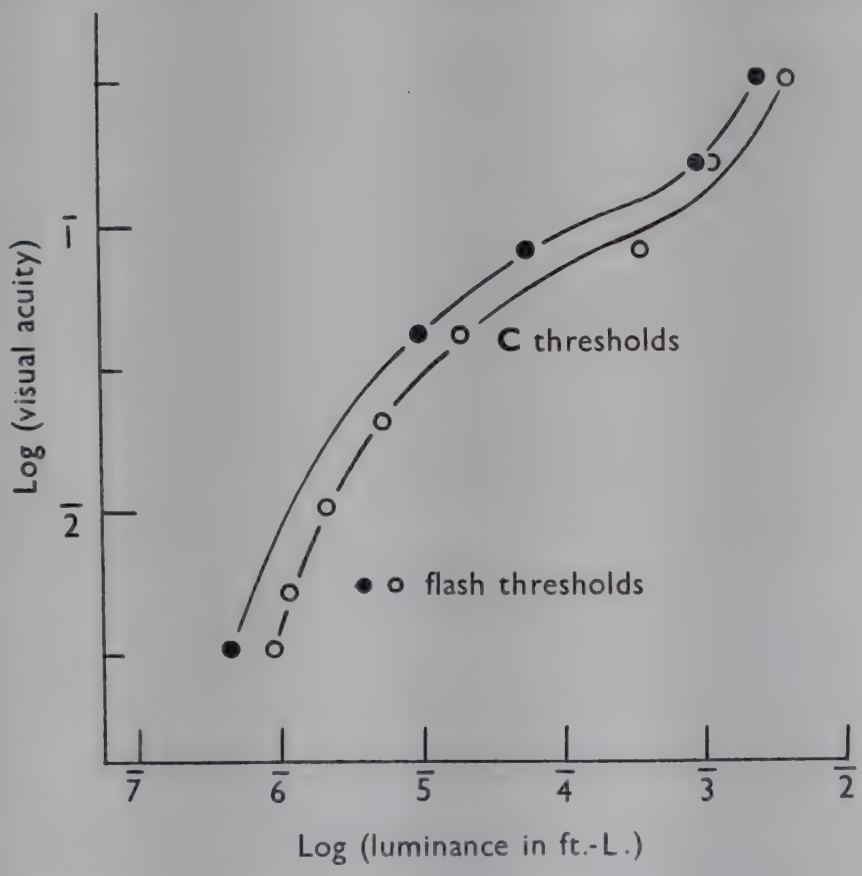

FIG. 10. The effect of dehydration on C and flash thresholds of Subject 9. ○ = measurements made after experimental dehydration. ● = measurements made under normal conditions.

A reversible translation (0·24 and 0·47 log unit in two experiments) of the foveal acuity curve as a whole towards higher intensities, without vertical shift, has been found to be produced in man by reduced oxygen tension in the air (McFarland and Halperin, 1940). During the present investigation a displacement of the whole acuity curve and of the flash threshold was found in Subject 9

who took part in a dehydration experiment. For this experiment his acuity and flash thresholds were measured twice, first after 'dehydration', and again a month later. Both his C and flash threshold values were on the average 0·25 log unit lower on the second occasion (Fig. 10).

Differences in the quality of the refractive system of the eye probably have little influence in the present range of measurements, since all subjects have been selected as having, in bright light, an acuity (0·7, 0·9, 1 or more) at least four times higher than the highest acuities ($\frac{1}{8}$ or $\frac{1}{6}$) considered here.

'Night myopia' is unlikely to have seriously affected the present measurements because the object/eye distance was 114·6 cm. In night vision the emmetropic eye requires a correction of the order of −1 dioptre, so that a viewing distance of about 1 metre compensates for this defect.

THE PREDICTIVE VALUE OF THRESHOLD MEASUREMENTS

If the filter factor theory is substantially correct, there is little fundamental basis on which to choose between the flash threshold and the thresholds of various C test objects as an index of the general scotopic efficiency of a subject's vision. The choice must be made on practical grounds of convenience and accuracy. The flash threshold is easier and quicker to measure than the C thresholds. On account of its correlation with the latter, it should have good predictive value for acuity at given luminances up to acuity $\frac{1}{6}$.

In practice, the luminance level is usually determined by external conditions. Thus what is required is the prediction, not of the C thresholds, but of the visual acuities of different subjects at a given luminance level. It has been seen in Part I, that there is a greater variation among individual acuities at low luminance levels than at levels corresponding approximately to acuity $\frac{1}{8}$. Thus, as an index of performance over the whole range of rod vision, the visual acuity in a range near $\frac{1}{8}$ may be less useful than a measurement made at a lower level. Accordingly, the fact that the flash threshold correlates less closely with the 8′ and 6′ C thresholds than with C threshold measurements made with larger test objects may reduce but little its value for predictive purposes.

The C threshold measurements, particularly those made at higher luminances, are subject to large errors, and therefore entail long experiments if reasonable accuracy is to be obtained. Further, the difficulty of the visual task makes them unsuitable for use with untrained or inattentive subjects. On every score, therefore, the absolute threshold measured by the 'fixation-and-flash' method would seem the most satisfactory index of performance.

Sensitivity and Perceptual Efficiency

Strictly speaking, the above conclusion is valid only for the present subjects and the present laboratory experiments. Moreover, it should be pointed out that it is apparently at variance with the conclusion generally reached as a result of the studies of night-vision tests made for the Armed Services during the last war. Thus Berry (1949) writes, " . . . it became clear soon after the beginning of these studies that something more than a patch of light as a test object was necessary if a test had to have even a modicum of meaning as an indicator of night visual ability."

What is meant here by 'night visual ability' is 'efficiency of visual perception at the luminances encountered at night'. The efficiency of a particular individual in the performance of a specific task under such conditions (e.g. identifying enemy ships at sea) need not necessarily be a function of visual sensitivity alone

—just as the efficiency of an individual at high luminances (e.g. in identifying a genuine Vermeer) need not necessarily be a function only of colour vision and daylight acuity. The experiments reported in Part IV, however, will show that the 'flash threshold' can also be a good index of performance in certain situations of considerable perceptual complexity. On the basis of these experiments and of the filter factor theory, conclusions such as that reached by Berry may not be quite as safely established as is often believed.

In the above-mentioned war-time studies, high correlations were rarely observed between night-vision tests of different types, or between tests and experiments on night performance of personnel in the field.* In such tests and experiments made on service personnel, it is possible that the variability of the experimental results was often so high that, as explained in Part II, correlations between various visual functions might have become unobservable even though they would have been observed if the measurements could have been made more accurately.

The question then arises whether the measurements could indeed have given more accurate results. In the case of the laboratory experiments of this Report, strict controls can be applied and the accuracy can be increased up to a certain point. This sheds little light in the case of tests or field experiments made with service personnel, however. In the latter case, owing to various psychological factors not operative in laboratory experiments, there might be such an inherent variability of performance that all tests might be valueless in practice except for eliminating the 'night-blind'. Conversely, a simple test such as the flash threshold might in fact be capable of predicting the mean night visual performance of a given member of personnel. Such possibilities can only be tested by further experiments. These experiments should include the study of subjects with very low flash thresholds, that is, with very high sensitivity, in order to find out whether, in tasks with strong motivation, their performance after training is *on the average* better than that of subjects with a low sensitivity—as was found in laboratory experiments to be described in Part IV.

The general idea of the filter factor theory was current before the war in the laboratory of the late Selig Hecht, and seems to have been shared by a number of other biologists. The use of the term 'filter factor' in the present connexion probably originates from the Report by Hartline and McDonald circulated in 1943 and reproduced here as Appendix C.

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* Such psychological factors as 'motivation' are of great importance in experiments on service personnel. This is illustrated by the following extracts from an article entitled 'Sharp eyesight in the dark: successful action by coastal forces' published in *The Times* on 22nd September, 1942: 'The enemy was first sighted by the senior officer himself at a distance of some four miles, though nobody else could see them, and an M.G.B. sent to search failed to locate them. Lieutenant Lloyd [the senior officer] was convinced he was right, and shortly afterwards sighted the enemy again, distinguishing three ships. At midnight his observation was confirmed and the enemy was identified as four *flak* ships, and at once engaged . . . Some people are endowed by nature with sharper eyesight than others, but it is not an unusual phenomenon for responsibility to stimulate the power of observation. Many naval officers have noticed that objects of interest at sea, particularly in the dark or in low visibility, are very frequently sighted by the officer on whom the responsibility for action will rest, before they are reported by look-outs.' Although such observations are not based on statistical evidence, and although other factors besides motivation are probably involved, there is no doubt that experiments on service personnel are more likely to be affected by variations in the degree of motivation than are experiments of the kind described in this Report.

IV. The Relationship between Sensory and Perceptual Efficiency

AIM OF THE EXPERIMENTS

The preceding experiments on the 'flash' threshold and the C thresholds are concerned with the 'sensory' efficiency of the subjects; the visual efficiency of a man using his eyes under natural conditions, however—for instance a night look-out on board ship—involves many psychological elements absent from the simple sensory measurement and could therefore be called 'perceptual' efficiency. Since, from a psychological introspective standpoint, even the simplest threshold measurement is a task of considerable complexity for the subject, it might perhaps be argued that the words 'sensory' and 'perceptual' here refer to different degrees of complexity rather than to differences in kind between perceptual situations; but even if this argument were accepted, the difference in degree would be sufficient to justify the use of the two different terms.

The following laboratory experiments were made to study the relationship between sensory and perceptual efficiency in a number of subjects who underwent progressive training during the measurements. The sensory efficiency was estimated on the basis of the 'flash absolute threshold' of each subject, measured in a manner similar to that described in Part II; this test was chosen because it is one of the simplest possible measurements of sensory efficiency. The perceptual efficiency was estimated by asking the subject to describe a complicated picture shown to him in dim light under controlled conditions; the score for the perceptual efficiency of the subject was taken as the number of correct statements, minus the number of wrong statements, made by the subject in describing the objects in the picture. The measurement of both sensory and perceptual efficiencies was made after the subjects had been dark-adapted for at least half an hour.

Previous studies on sensory and perceptual efficiency have often failed to demonstrate a significant correlation between the two; but it has also been reported that no correlation could be found between one kind of visual sensory efficiency and another, whereas in Parts I and II of this Report a correlation was found between such efficiencies. Even the simplest measurements of sensory efficiency may suffer from a large inherent inaccuracy; the efficiency must therefore be estimated by a statistical method, and the estimated value may be considerably in error if the number of trials on which this determination is based is small. Accordingly, the correlation observed between certain estimates of sensory efficiencies may fail to appear significant simply because of experimental errors, even though a high correlation does exist between the exact values of the sensory efficiencies. Similarly, failure to find a correlation between sensory efficiency and perceptual efficiency may be due simply to the inaccuracy of the measurements of one or the other. In the present experiments, sensory efficiency was estimated in the same way as in Part II, in order to obtain the same degree of accuracy, and the test for perceptual efficiency was conducted in a special way. One of the reasons for choosing a complicated picture as material for the perceptual efficiency test was that the results would then represent a statistical average of the performance of the subject in connexion with the many different parts and aspects of the picture. Such perceptual material may thus lead to results more consistent and reliable than those sometimes obtained using much simpler material.

PLATE I

Fitzwilliam Museum, Cambridge.

'Hudibras beats Sidrophel and his man Whacum', William Hogarth (1726): Picture used in the experiments on perceptual efficiency. (Part IV.)

SUBJECTS

Nineteen subjects—15 men and 4 women—took part in the experiments; they were given numbers from 45 to 63. Most of the subjects were between 20 and 30 years old. Approximately half of them had been subjects in the experiments of Parts I and II; the others had no previous experience of such tests. Most of the subjects were university students, two were research workers in psychology, one was an archaeologist, and one was a leading stoker, R.N. They had all volunteered for the experiments and seemed keen to do their best.

ESTIMATING SENSORY EFFICIENCY

Apparatus and Method

The instrument used was a portable Hecht-Shlaer adaptometer Model 3, as used by the Royal Canadian Navy for the selection of night look-outs, etc. (Solandt and Best, 1943). This instrument presents to the subject, who uses both eyes, a red fixation point. When the subject or the experimenter presses a lever, a pendulum shutter is released and a circular test field 3° in diameter, placed 7° below the fixation point, is exposed in violet light for a duration of 0·2 sec. The experimental conditions were thus very similar to those described in Part II, but the distance of the eyes from the test field was about 30 cm. instead of 115 cm. and violet light* was used instead of white light; this light, however, always looked colourless to the dark-adapted subject when keeping proper fixation. The brightness of the test field could be chosen at will by the experimenter, who read its value on a scale. This scale gave the logarithm to base 10 of the luminance of the test field expressed in micro-microlamberts.

The measurements were made in essentially the same way as those of Part II. The experimenter set the instrument at various luminance levels unknown to the subject, and for each luminance the subject when 'ready' pressed the lever while looking at the fixation point, and then reported whether he had seen the test field or not. The various brightnesses were presented at random and mixed with a few 'blanks', i.e., unknown to the subject the light was completely cut off from the test field for some of the exposures. The logarithm of the luminance value corresponding approximately to 50 per cent frequency of seeing was estimated by the Hartline-McDonald method, as in Part II. We will call this logarithmic value the 'H.S. (Hecht-Shlaer) flash threshold', the luminance being expressed in micro-microlamberts as on the scale of the instrument. The flash thresholds of the 19 subjects are given in Table 7 (p. 36).

The Hecht-Shlaer adaptometer, Model 3, contains its own system of calibration of the source of light. The glass neutral wedges, the pendulum shutter and other features of the instrument also help to make it accurate and reliable.

ESTIMATING PERCEPTUAL EFFICIENCY

Apparatus and Method

The subject was seated at a small table. An enlarged photographic copy (54 × 37 cm.) of the engraving by Hogarth entitled 'Hudibras beats Sidrophel and his man Whacum' (Plate I, opposite) was hung in front of him at a fixed distance from the table and about 1 m. distant from the subject's eyes. It was lit by the light source used in the experiments of Parts I and II. This source was placed above and behind the subject so that the light reached the picture over

* The use of violet light in this part of the experiment is discussed in Appendix A.

his head (Fig. 11). As in Parts I and II, the light emitted by the source was white, no colour filter being used, and its colour temperature was about 2440° K. The illumination in the plane of the picture could be selected at will by adjusting the neutral wedges, but it was always kept constant for the duration of each test. The greater number of the experiments were made at a fixed illumination which will here be called the 'standard illumination'. When the

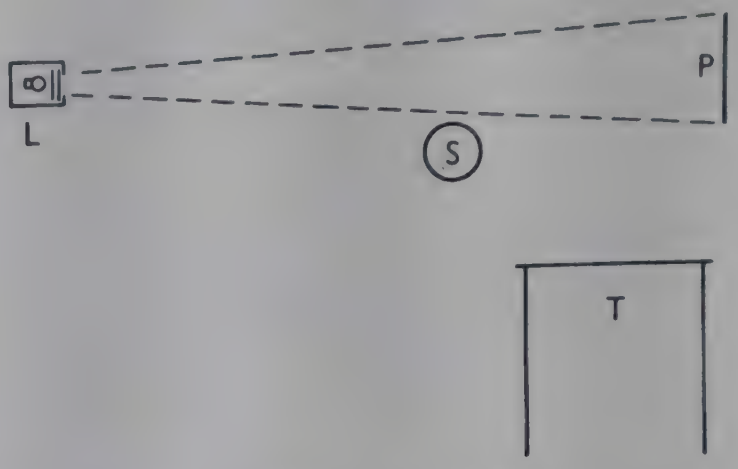

FIG. 11. Diagram (elevation) of apparatus used for the experiments on perceptual efficiency. L = light source, P = picture, T = table, S = position of subject's head.

picture was lit by this standard illumination, the luminance of the table-cloth depicted in the centre of the picture was about 0·00016 ft.-L. (0·00055 cd/m²). According to the graph of Fig. 3 (p. 10), the mean visual acuity is about 0·1 at this level. The small table at which the subject was sitting kept him at an approximately constant distance from the picture while allowing him to sit in a natural way, no head rest being used.

After the subject had been in complete darkness for about half an hour, the light was turned on and he was told: "This is an old print representing the interior of a magician's den. It may be expected to be full of people, animals, or objects of a familiar or unfamiliar kind, but it does not contain anything specifically modern. You are asked to say what you see in this picture. Your report should be similar to evidence given in a court of law. You should name and describe people, things, etc. Do not make vague statements, such as: 'I see a white patch but I do not know what it is', as these are of no practical value." The subject was encouraged to mention all the details he could see: for instance, if he saw a man, to tell all he could distinguish concerning his face, attitude, clothes, etc. The experimenter wrote down the description of the picture as given by the subject. This usually took about a quarter of an hour.

It seems that the subjects took a real interest in this test, since at the end of the experiments nearly all of them asked to see the picture in ordinary light to verify their observations. The picture was not shown to them until all the experiments were completed.

A second test of perceptual efficiency was made in exactly the same manner as the first, on 9 of the subjects. Measurement of the H.S. flash threshold was repeated in only 3 cases, when the difference between the second and the first measurements was found to be insignificant.

For this experiment it seemed preferable to use a print by an artist such as Hogarth, who is considered a truthful draughtsman, rather than a drawing made specially for the purpose. In the experimental conditions, if a subject having a high perceptual ability were shown a drawing of indifferent quality

he might, precisely because of his high degree of perceptual ability, fail to perceive what the draughtsman wished to represent. A less critical observer, on the other hand, might give answers in better agreement with the draughtsman's intentions because he would fail to notice inconsistencies which puzzled the other subject. An arrangement similar to a theatre setting including dummies would have had the same disadvantage as an indifferent drawing, for in general theatre settings and dummies look very artificial to a critical observer. The ideal solution would have been to use an actual scene from life with real objects and people, but here this would have been impracticable. As to using a photograph of a real scene, this might have led to difficulties of the same kind as those arising from the use of drawings, because, contrary to widespread opinion, the photographic camera does sometimes 'lie', or produce results unintelligible to the eye.

Scoring

Accurate scoring of the results of this test presented difficulties, but the differences between the reports made by the various subjects were so marked that they indicated unmistakably the trend of the results, in spite of uncertainty in the exact values.

The scores were calculated according to the following rules:

(a) A mark was given for each correct statement made in the description of the picture, and a mark was deducted for every wrong statement.

(b) Some statements were considered to consist of several statements and were given several marks. Thus "human figure" was given 2 marks; "a man", that is, 'a male human figure', was given 3 marks. If a man was described as a woman, 2 marks were given for 'human figure', which is a correct statement and 1 mark was deducted for 'female' which is a wrong statement; thus the final score was 2— 1 = 1 mark.

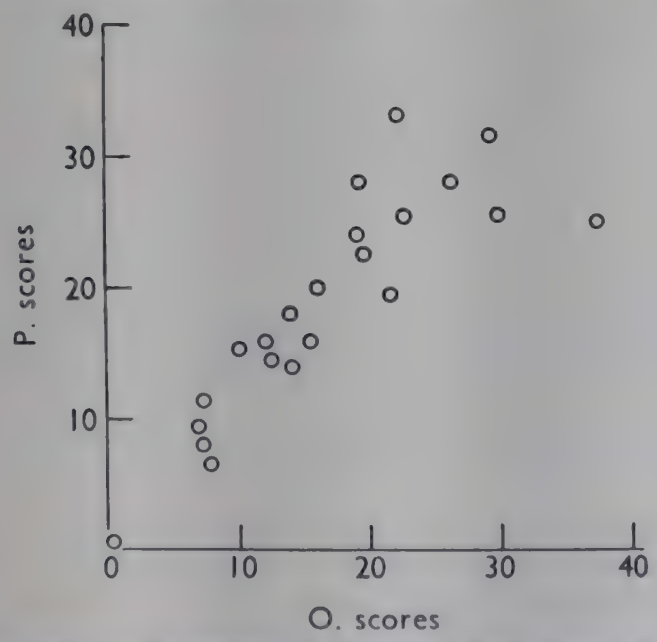

FIG. 12. Diagram showing the correlation between the perceptual efficiency scores (P. and O.) estimated by two different experimenters (Table 7).

(c) Some vague statements were given half a mark; an example is the statement "a long horizontal object hanging from the ceiling" for the stuffed crocodile.

The scores obtained according to the above three principles were recorded by one of the authors (M. H. P.), and will be called here 'P.' scores.

A certain number of reports were scored independently by another of the authors (E. F. O'D.) according to the general rule (a) previous page. These scores will be called 'O.' scores. The correlation between the 'P.' and the 'O.' scores is shown in the dot diagram, Fig. 12, where it is seen that there is a reasonable agreement between the two methods.

Results

The results of the experiments are given in Table 7.

TABLE 7

Results of experiments on the relationship between perceptual and sensory efficiency

Subject	Sex	H.S. Flash threshold	Perceptual efficiency 1st test—scores		Perceptual efficiency 2nd test—scores		Perceptual efficiency with augmented lighting	
			O.	P.	O.	P.	score P.	log luminance increased by
45	M.	1·90	12	16	—	32	37	0·20
46*	M.	1·95	22½	25½	—	25	28	0·15†
47*	F.	2·45	8	6½	—	15½	31½	0·75
48	M.	3·70	½	½	—	—	—	—
49	M.	2·60	7½	8	—	4½	35	0·90
50*	M.	2·00	19½	22½	29½	25½	—	—
51	M.	1·75	21½	19½	26	28	—	—
52	M.	2·05	14	18	37	24½	—	—
53	F.	1·70	7½	11½	22	33	—	—
54	F.	2·15	14	14	—	22½	36½	0·45
55	M.	1·90	19	24				
56	M.	2·23	16	20				
57	M.	2·20	15½	16				
58	M.	1·70	29	31½				
59*	M.	1·77	—	31½				
60	F.	1·80	12½	14½				
61	M.	2·05	10	15½				
62*	M.	2·15	7	9½				
63	M.	2·00	19	28				

* Subjects with spectacles.

† For Subject 46, the increase of luminance should have been 0·25 instead of 0·15 log unit; this small experimental error may have led to a rather low P. score.

The report given by Subject 58 who had high sensory and perceptual efficiencies is reproduced here as a specimen:

Subject 58.

H.S. Flash threshold: 1·7.

First Hogarth test, standard illumination

Report: Doorway, three steps down from it. Man, two legs, stooping forward, going out. Long tail coat, breeches (gaiters?). Below him an object, open metal work. Man standing, legs astride. Table, open book on it. Above the book a light burning as if fixed into the wall. Above, a lengthy object, whiter underneath and having vertical black lines across the white part. Other object, oval, like a light shade. Other similar object, smaller, on the left, above the long thing. Other side of table human figure, white garment, or beard. Facing the man with legs astride. On the floor, cross with triple cross beam, the bottom one longer. Long oval object near to that. Something below that casting a shadow. On the left, human figure, standing, dark trousers, white shirt. Black cocked hat. Standing with

arm outstretched over globe. Globe. On the top, white lines. Metal rim like Saturn. On a raised platform, 2 shallow steps. Left, window, black. Left of globe, small human figure, kneeling. White bits of curtain about the heads of the people on the left. Bedspread or table-cloth. Pillow on top of the table or bed. (P. *Score*: 31½)

At the levels of illumination used in the experiments a great many details of the picture remained unseen by all the subjects, as can be seen, for instance, by comparing the preceding report with the picture as reproduced in Plate I. The proportion of undetected details is so large that it seems certain that no subject, however high his sensory and perceptual efficiency, could have described them all under the conditions of the experiments. The performance of the subjects therefore could not have been restricted by the actual limited perceptual contents of the picture.

Subject 48, who said he was 'night blind', had an exceptionally low sensory efficiency. He came for one experiment only. His report follows:

Subject 48.
H.S. Flash threshold: 3·7.
Hogarth test, standard illumination

Report: Square of light [this was the picture itself, which was framed in black paper]. On the right, dark patch: rock? tree? branches? White patches: windows? [this was the table-cloth].

(This subject could not recognize any object in the picture; however, he could see the shadow of the experimenter's hand when cast on the picture.) (P. *Score*: ½)

First test. Parts (*a*) and (*b*) of Fig. 13 give respectively the P. and O. perceptual efficiency scores of the first experiment made by the subjects, plotted against the values of their H.S. flash thresholds determined as explained above. The higher the H.S. flash threshold of a subject, the lower his sensitivity; high H.S. flash threshold values thus correspond to low sensory efficiencies.

The following conclusions may be drawn from an examination of Fig. 13:

(a) There is often a wide scatter of perceptual efficiencies among subjects having the same sensory efficiency. This is particularly noticeable for the subjects with high sensory efficiencies. Thus for this first test the relationship between sensory efficiency and perceptual efficiency is not well defined. Perceptual efficiency cannot be regarded as a function of sensory efficiency only; other factors must be involved.

(b) There is, nevertheless, a relationship between perceptual efficiency and sensory efficiency. High perceptual efficiencies occur only among subjects with high sensory efficiencies (i.e. low H.S. flash threshold values). Low sensory efficiencies are invariably associated with low perceptual efficiencies. But although some subjects with high sensory efficiencies have high perceptual efficiencies, others have low perceptual efficiencies.

These observations may be interpreted by supposing that perceptual efficiency is limited by sensory efficiency, but is also affected by other factors, the influence of which may in some cases be very marked. If this interpretation is correct, the relationship between sensory and perceptual efficiency should become much closer if the effect of the other factors could be reduced. It was thought that training would tend to make these variable factors more nearly equal, and the test was therefore repeated on a number of subjects.

Second test: effect of training. Fig. 14 gives the perceptual efficiency scores of the nine subjects of the second test (large circles) plotted against the H.S. flash thresholds of these subjects. The figure also gives the perceptual efficiency scores of the first test for the same subjects (small circles). It is seen that all the subjects

but two gave a higher perceptual efficiency score at the second test, the two exceptional subjects giving a lower score. While the amount by which the scores increased was variable, comparison of Fig. 14 with Fig. 13*a* reveals the following tendency: In each group of subjects having fairly similar H.S. flash threshold values the subjects who, in the first test, gave a lower perceptual efficiency score often showed a greater increase in their perceptual efficiency scores than

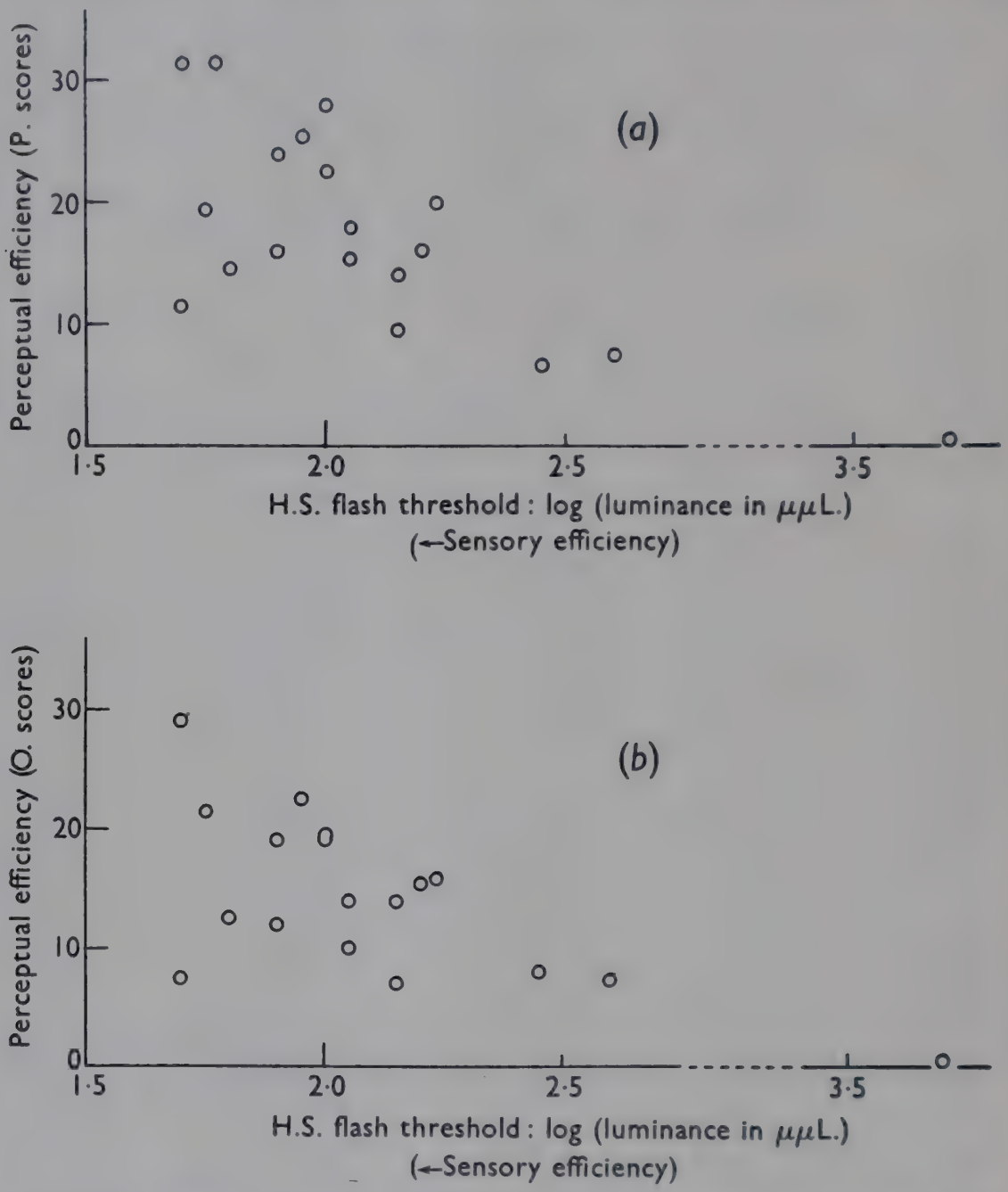

FIG. 13. Perceptual efficiency under standard illumination; (*a*) P. scores, and (*b*) O. scores, plotted against the H.S. flash threshold. The abscissa scale has been cut to include the results for Subject 48.

the others. This leads to a much more definite relationship between sensory efficiency and perceptual efficiency in the second than in the first series of tests. Perceptual efficiency after training tends to become a function of sensory efficiency only. The other factors involved are reduced in importance, their influence being no greater than the order of accuracy of the scores.

Increased familiarity with the test thus results in all the subjects with similar sensory efficiency values now giving also fairly similar perceptual efficiency scores.

TESTING THE FILTER FACTOR THEORY

In these experiments into the relationship between perceptual and sensory efficiency an important feature was that control of all experimental conditions, physical, physiological and psychological, should be as complete as possible. The results mentioned so far suggest that, after training, differences in the sensory efficiency of the subjects are the main cause of differences in their

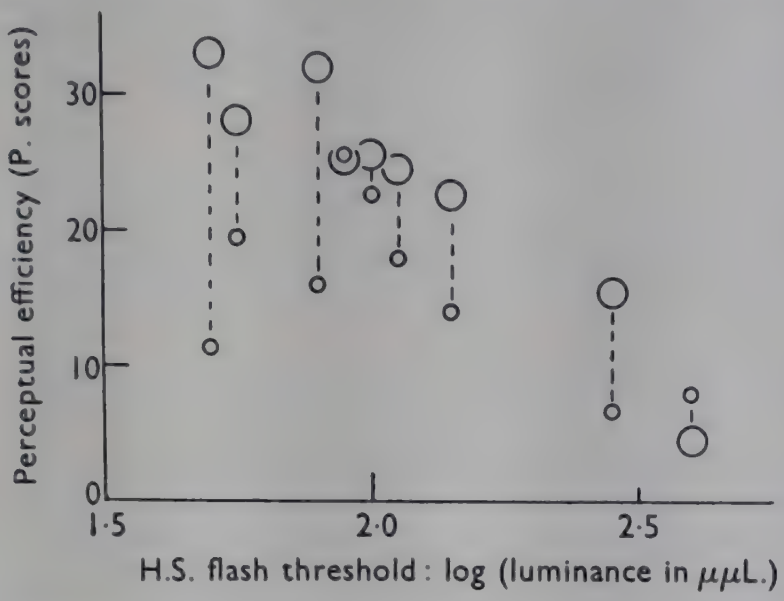

FIG. 14. The effect of training on perceptual efficiency. The small circles reproduce for 9 subjects the results of the first perceptual efficiency test (Fig. 13*a*). The large circles represent the results of the second test on these subjects. Illumination was standard for both tests.

perceptual efficiency. In Part III the filter factor theory was suggested as an interpretation of the results of Parts I and II. According to this theory, the subjects would behave as if they were very similar in all respects except that some of them would always need k times more light than others to perform the same visual task. The validity of this theory was tested with regard to the experiments on perceptual efficiency.

In both series of tests just described the picture was presented to all the subjects under the same standard illumination, and their perceptual efficiency scores were then derived from their individual reports. Sensory efficiency, on the other hand, was estimated from the H.S. flash threshold for each subject, that is, we measured the actual luminance required by each subject to enable him to see the test field; thus the luminance of the test field was adjusted to the needs of the subjects until they could all perform the same visual task. For example, it was found that the most sensitive of the subjects who had performed the second series of tests, Subject 53, had a H.S. flash threshold equal to 1·7, and that the least sensitive subject, Subject 49, had a H.S. flash threshold equal to 2·6 (Table 7). The difference ($2{\cdot}6 - 1{\cdot}7 = 0{\cdot}9$) is equal to log 8, which means that Subject 49 needed eight times more light than Subject 53 to detect the light flash in the adaptometer. According to the filter factor theory, if Subject 49 were shown the picture under an illumination eight times the standard illumination, that is eight times that used for Subject 53, he should be able to see the picture as clearly as Subject 53 sees it under the standard illumination. This was tested experimentally, and in fact Subject 49 now gave a perceptual efficiency score equal to 35, a value which is very similar to the score, 33, given by Subject 53 under standard illumination. The perceptual efficiency score of Subject 49

had previously been measured under standard illumination and found equal to $4\frac{1}{2}$ on the second test. The following are the various reports he gave:

Subject 49.
H.S. flash threshold: 2·6.
First Hogarth test. Standard illumination

Report: Doorway. Man standing, one leg conspicuous, the other lost against the upright. Man wearing a three-cornered hat, on a lower level. Standing legs apart, or sitting and reading? (Shadow of leg?). In the middle of a shadow a dark thing, the size of a dog. A figure standing upright, not human, or uncertain? Wavy strokes on the foreground. Outlines conveying nothing definite. (P. *Score*: 8)

Second Hogarth test. Standard illumination

Report: Man standing on a platform; a doorway behind him; he is leaning over, against an upright. Steps. Fellow sitting, a leg in front of him, wearing a three-cornered hat (?). Reading something, bending over. Background of trees. Branch: a straight black line with a blob in it. Large bird with a tail and a big beak (toucan?). More trees on the left. (P. *Score*: $4\frac{1}{2}$)

Hogarth test with lighting augmented according to sensory efficiency (illumination equal to eight times the standard illumination)

Report: Man on top of the steps, three at least [as reported in the second test made with standard illumination]. Below the steps, something in the foreground. Man striding, legs apart, wearing a three-cornered hat, looking down, holding something in his hand. Bed, shadow at the bottom. The blob is a shadow due to the blankets being disarranged. Other man, legs in black trousers, wearing a light shirt and a flat cap (?) in the attitude of somebody warming his hands towards a globe. Globe of the world having a rim around the equator. Window looking into blackness, window sill. White figure, looking like a Greek marble, no hat, round head, as if moving away from the people on right. White patch above the bed. An oddity, light below, dark above, above the white patch. Open book on the bed. Cross of Lorraine with 3 or 2 cross bars. Logs of wood. (P. *Score*: 35)

These reports illustrate the fact that, while perceptual efficiency scores cannot be highly accurate, many of the differences observed under conditions of standard illumination are undoubtedly significant. Subject 49 gave perceptual efficiency scores of 8 (first test) and $4\frac{1}{2}$ (second test) under standard illumination. After 'compensation' he gave a score of 35. The difference between the first two results and the last result is quite unmistakable; the records show that the subject undoubtedly saw much more in the last than in the first two tests. The difference between the first test score, 8, and the second test score, $4\frac{1}{2}$, may be attributed to an observed difference in the attitude of the subject, who felt more confident the second time, stating that he was telling 'what *was* there'. He was in fact over-confident, which led to errors with consequent loss of marks.

Experiments were made with a total of 5 subjects in accordance with this principle; thus a subject X having a H.S. flash threshold value k times that of Subject 53 would be shown the picture under an illumination k times the standard illumination, the illumination for Subject 53 being of course standard. The scores are given in Table 7 (p. 36) together with the increase in luminance for each subject. Fig. 15 represents the results for these five subjects in graphic form. By comparing this figure with Fig. 14 (p. 39) it is seen that the differences in perceptual efficiency scores are now of about the same order as the errors of the scoring method. The data show no trend in the perceptual efficiency with increasing H.S. flash thresholds.

Thus it proved possible to compensate for differences in sensory efficiency simply by making the illumination of the picture proportional, for each subject, to the luminance corresponding to his H.S. flash threshold. Under these

conditions all the subjects gave perceptual efficiency scores of similar magnitude, as predicted by the filter factor theory.

It will be noted that this finding is similar to the results concerning flash threshold and visual acuity given in Parts I and II. These experiments showed that if the background luminance is made proportional to the luminance corresponding to the flash threshold of each subject, all subjects are able to see

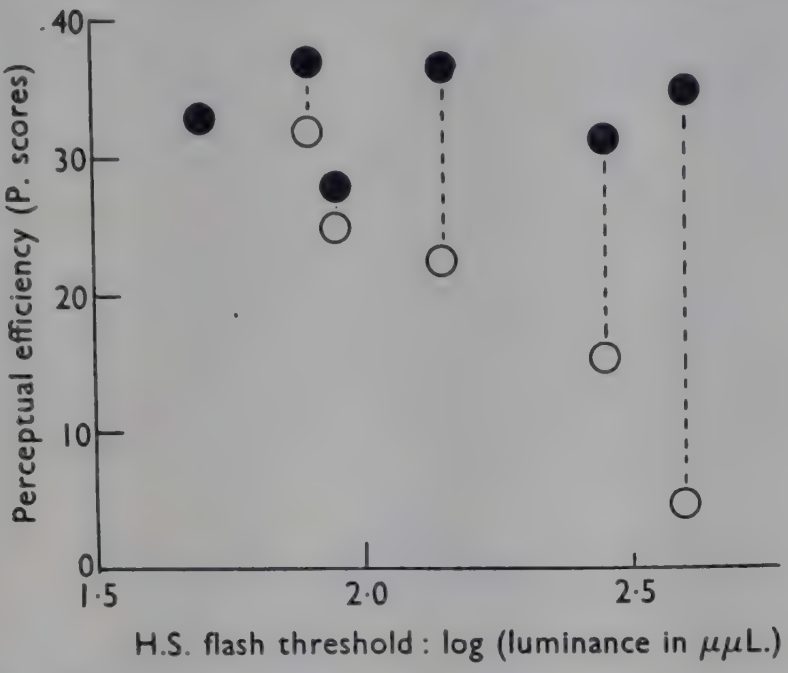

FIG. 15. The effect on perceptual efficiency of augmented lighting to compensate for differences in sensory efficiency. The white circles represent the large circles of Fig. 14 for 5 of the subjects, i.e. results obtained under standard illumination. The black circles represent the scores for the same subjects under augmented lighting, as explained in the text (p. 40). For Subject 53, who gave the lowest H.S. threshold value, the lighting was not augmented; her P. score under standard illumination is represented by the black circle corresponding to 1·7 on the abscissa scale.

approximately the same size of C test object, that is, they all have approximately the same visual acuity. This corresponds to the results obtained here in studying perceptual efficiency under augmented lighting.

DISCUSSION

Under the present conditions, and after training, the differences in perceptual efficiency between subjects are mainly due to differences in sensory efficiency. When the differences in sensory efficiency are suitably compensated by giving to different subjects different quantities of light for the perceptual test according to their H.S. flash thresholds, the perceptual efficiency scores become much the same for all the subjects. The remaining differences between individual scores—which must be due in part to accidental errors—are then much smaller than the differences observed when no such compensation has been made for differences in sensory efficiency.

These results differ from those of some other investigations in which no correlations were found between sensory threshold measurements and performances in various perceptual tasks (Craik and Vernon, 1942). It would seem that differences in the experimental conditions may account for the different results. Two points may be mentioned in this connexion.

With regard to perceptual efficiency, the picture used in these experiments, although presenting a more complex pattern of physical stimuli than, say, a simple silhouette such as that used by Craik and Vernon, may nevertheless, on

account of its many internal connexions, lead to more regular psychologica responses than a silhouette. These internal connexions may, on the one hand tend to restrain the fancies of imaginative subjects and, on the other hand, ten to encourage cautious subjects to venture a description. Moreover, as explaine above (p. 32) regular results should be expected on purely statistical ground when a picture containing a large number of details is used.

With regard to sensory efficiency, the problem of the measurement of sensor absolute thresholds is admittedly a complex one, even when considered from th psychological point of view alone. However, the technique of fixation and flash used by Hecht and his collaborators for measuring the threshold, and adopte for this investigation, gives regular results from one subject to another whe applied to the measurements of the whole course of dark-adaptation, as i shown in Appendix A. Such regularity is not generally found using othe methods. Some of these methods give dark-adaptation curves presenting con siderable variations from one subject to another, particularly with regard to th cone-rod transition time. When for instance the course of dark-adaptation i measured using fixation and a *continuously exposed* test field, wide variation are observed from subject to subject. These may be due to differences in the accuracy of fixation from subject to subject, for if fixation is very accurate a continuously exposed test field, although clearly seen at first, becomes invisible after a few seconds—but becomes visible again if the subject moves his gaze away from the fixation point. In an accurately fixating subject, therefore, the threshold may sometimes fail to drop with increasing dark-adaptation, whereas this may not occur in a subject with less accurate fixation. This complication and others due mainly to the heterogeneity of the retina as regards its sensitivity, are avoided when measurements are made by the fixation-and-flash method. Using the latter method it seems that the physiological and psychological conditions of the experiments can be made to remain as nearly the same from one subject to another as can be achieved at the present time. Such a control of the factors involved in the measurement of the sensory threshold should tend to eliminate accidental differences between one subject and another, and to help in revealing any correlation which may exist between the threshold and other visual functions.

V. Acuity and Threshold Experiments in Relation to the Quantum Theory

According to modern physical theory, as is universally known, any emission or absorption of light takes place as a number of individual events, in each of which a single quantum of energy is exchanged. The preceding experiments on threshold and acuity acquire their full significance when interpreted in such terms; for it will be seen that in all these experiments the critical number of quanta involved is small. The general bearing of the quantum nature of light on the physiology of vision in man and in animals is discussed in a review article by Pirenne (1956).

LIGHT FLUX EMITTED BY THE GAP IN THE C TEST OBJECT

Even though the luminance of the large opal screen (Fig. 3, p. 10) required for a visual acuity of $\frac{1}{6}$ is about 2000 times greater than its luminance for the lowest acuity value studied in Part I, namely $\frac{1}{295}$, the light flux sent to the eye from the gap in the C test object (area *a*, Fig. 16) differs but little in the two

FIG. 16. Landolt C test object, showing the critical area *a*, the presence of which must be detected by the eye if the object is to be resolved.

cases, i.e., for the 295′ C and the 6′ C. In the former case the area of the gap is $(295)^2$ square minutes of arc and the luminance (Table 2, p. 9) is antilog $\bar{7}\cdot639$, the product of the two being 0·0379. In the latter case the corresponding values are $(6)^2$ and antilog $\bar{4}\cdot916$ and their product is 0·0297. Thus, in the case of the higher acuity, the light flux directly involved in the process of detecting the gap in the C not only is no larger, but is even somewhat smaller than for the lower acuity. Fig. 17 gives a logarithmic plot of similar products giving the critical light flux for the various acuities used in the experiment. It also gives the product (area × luminance) corresponding to the absolute threshold of the empty 47° field, in which case the corresponding acuity value, following the suggestion made in Part I, is taken as the reciprocal of the diameter of the whole field itself.

Chalmers (1915) had already pointed out that the critical light flux considered here was roughly constant over a broad acuity range, and approximately equal to the smallest light flux visible under the most favourable conditions. This is confirmed by the present calculations. Chalmers also estimated in terms of light quanta the energies involved, but here his calculations are not accurate.

Fig. 17 shows that between acuity $\frac{1}{295}$ and acuity $\frac{1}{3}$ the light flux from the gap in the C varies by less than 1 log unit and that it is minimal near acuity $\frac{1}{24}$. This light flux would be quite constant and independent of the acuity value if the slope of the curve of log acuity versus log luminance in Fig. 3 (p. 10) were exactly 0·5, that is, if visual acuity were proportional to the square root of the luminance. The visual angle subtended at the eye by the gap in the test object

would then be inversely proportional to the square root of the luminance, the area of the gap would be inversely proportional to the luminance, and the product (area × luminance) would of course be constant. The actual curve of Fig. 17 constitutes a very rough approximation to this simple situation. The case of the 47° field deviates strongly from it, the total threshold flux in this case being 2·5 log units higher than the flux from the gap of the 24′ C.

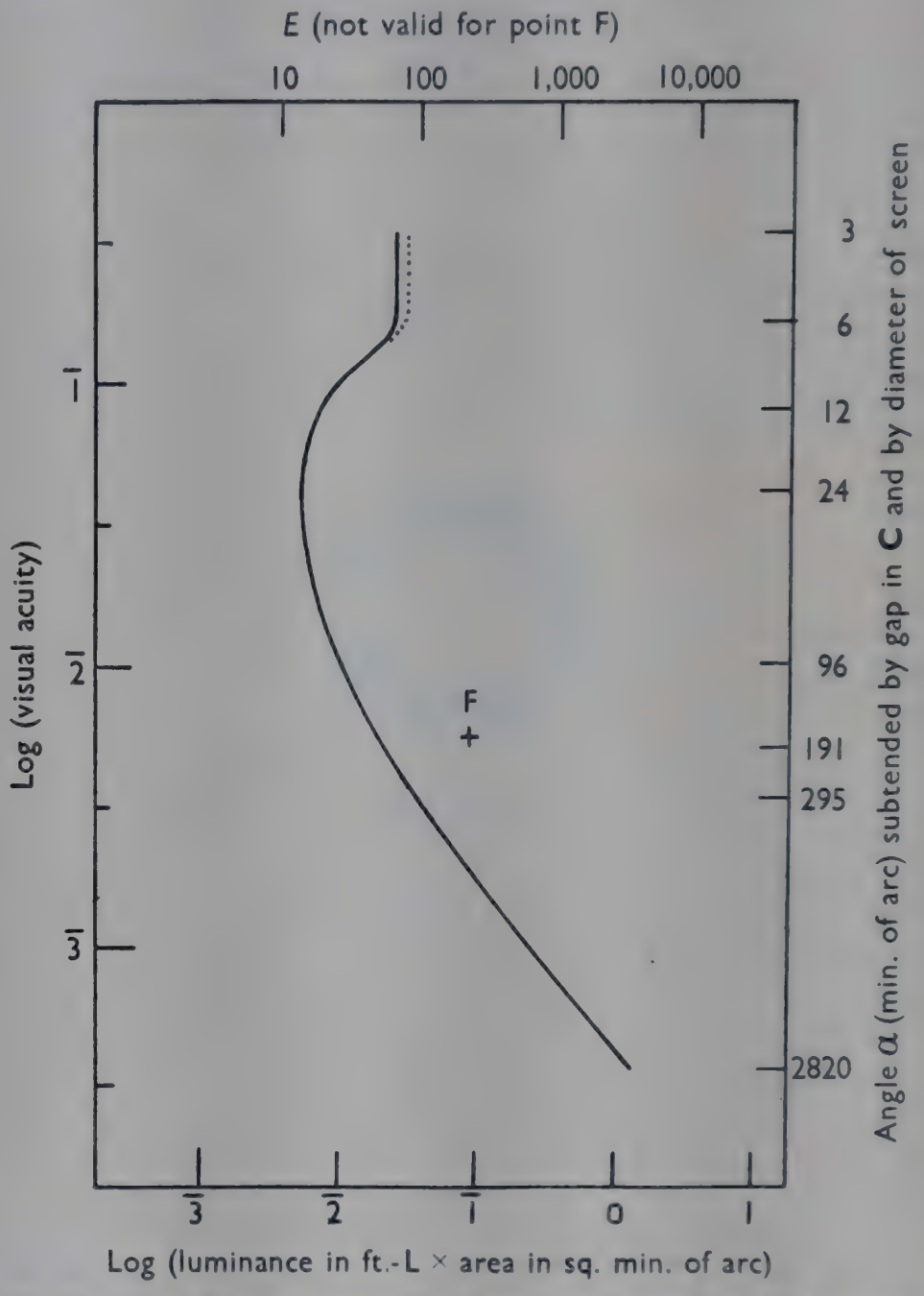

FIG. 17. Variation of the amount of light reaching the eye from the gap *a* in the C test object (Fig. 16), and from the 47° field, for various visual acuities; the dotted line gives the same values uncorrected for changes in pupil size. The corresponding value for the 3° flash is shown at point F. The upper abscissa scale gives the values for energy *E* (in light quanta per 0·1 sec.) of Table 8 (p. 48), but this scale refers only to the values for the C and 47° field experiments, and not to the flash experiments. However the point F is correctly placed on the lower scale, which is independent of time units.

Fig. 17 also gives the product (area × luminance) corresponding to the 3° field used to measure the 'flash threshold'. Here, however, we are dealing with a flash of light lasting for 0·2 sec. instead of a continuous flux. In order to compare the above values relating to the gap in the C with that corresponding to the 'flash threshold', a proper physiological unit of time must be chosen. It is pointed out in Appendix A that on account of the saccadic eye movements, the retina

takes 'snapshots' with exposure times of the order of 0·1 to 0·3 sec., each snapshot corresponding to a fixation pause. This is the order of our flash duration, 0·2 sec., and we may first take it that the duration of each of the eye's fixation pauses in the acuity experiments was also 0·2 sec. The amounts of light delivered by the gaps of the C's in each fixation pause or elementary exposure of the retina can then be compared at once with the light content of the flash on the basis of Fig. 17, since the time units are the same in all cases. It is seen that the amount of light so calculated for the C experiments is always smaller than the light content of the flash under threshold conditions. It must be noted, however, that the conditions of area, duration, etc., chosen here for the flash threshold, are not those which should be used for the determination of the minimum amount of light necessary for vision; this requires a smaller area and a shorter exposure. The total amount of light given off in 0·2 sec. by the 47° field at the limit of visibility is larger than the light content of the flash used here.

The retinal action time, which is of the order of 0·1 rather than 0·2 sec., may be a more appropriate unit of time than the duration of the fixation pauses. The above conclusions however are but little affected if we take 0·1 sec. as the effective duration of each elementary exposure of the retina and if we then calculate the light content the flash should have had if its duration had been 0·1 instead of 0·2 sec. The results of Graham and Margaria (1935) show that this change in flash duration would have led to a decrease of about 0·16 log unit in the total light content of the threshold flash. Thus the light content of a 0·1 sec. flash at the absolute threshold would still be higher than the amounts of light emitted during 0·1 sec. by the gap of any of our test objects at their threshold of visibility; the flash light content would be about 10 times higher than the amount which corresponds to the 24′ C.

All this leads to a new understanding of the observed correlations between the flash threshold and the C thresholds measured at 'supraliminal' luminance levels. The *luminance* corresponding to acuity $\frac{1}{6}$ is about 4000 times the luminance corresponding to the absolute threshold of the 47° field itself, and in comparison with the latter it can obviously be described as 'supraliminal'. But the actual light quantities apparently involved in the process of seeing the gap in the C (plotted in Fig. 17) are no more 'supraliminal' than those involved in the flash measurement of the absolute threshold; they are even lower than the latter. This fact will assume its full significance when the quantities of light are translated into natural units of radiant energy.

MONOCHROMATIC RADIANT ENERGY EQUIVALENT TO WHITE LIGHT

As is universally known, the amount of light energy required to determine a given response in the scotopic visual system is minimal for monochromatic light of wave-length $\lambda = 0{\cdot}51\mu$. On the basis of the relative scotopic luminous efficiency function adopted by the Commission Internationale de l'Eclairage (International Commission on Illumination) (1951), it is possible to calculate the amount of radiant energy of wave-length $\lambda = 0{\cdot}51\mu$ which has the same effectiveness on the retinal rod mechanism as a given amount of white light. Thus for light of the same spectral distribution as that used in the present experiments (colour T = 2400° K), a luminance of 10^{-6} cd/m^2 is equivalent in light of $0{\cdot}51\mu$ to an energy flux of $6{\cdot}94 \times 10^{-7}$ erg per sec. per unit solid angle (steradian) per cm^2 of the field (Appendix B, p. 67). This luminance gives the order of magnitude of the absolute threshold for a large continuously-exposed field. It has been found in Part I (p. 8) that the mean value of the threshold for

the 47° field in 22 young subjects was $\bar{7}\cdot87$ log units (cd/m²) in white light; this is equivalent to

$$L = 5\cdot1 \times 10^{-7} \text{ erg } (0\cdot51\mu)/\text{sec} \times \text{steradian} \times \text{cm}^2 \text{ (field)} \quad (4)$$

It may be pointed out that near the threshold the 47° field has the same appearance and colour (whitish or greyish) for white light and for light of $0\cdot51\mu$, while of course in cone vision the spectral light would look coloured—blue-green in the present case. This is evidence that rod vision alone is involved under those conditions. The absolute threshold for the 47° field was measured in one subject first with white light, and then with a narrow band of spectral light, near $0\cdot5\mu$, transmitted by a colour filter placed in front of the electric lamp of the apparatus. Both measurements were made at the same sitting. The results were in excellent agreement with the above-mentioned calculations after a minor correction had been made for the fact that the optical wedges were not exactly neutral (Denton and Pirenne, 1954a). In the present calculations this correction is neglected, so that the energy values to be discussed here may be slightly too high (Appendix B, p. 67).

When the luminance of a visual field is L, the illumination D in the retinal image of this field is given (Le Grand, 1948) as:

$$D = 0\cdot36 \times \tau \times s \times L \quad (5)$$

where τ is the transmission factor of the eye media from the outer surface of the cornea to the retina, and s is the area of the pupil in cm². The factor τ varies with the wave-length but its values are not known with a high degree of accuracy (Le Grand, 1948). A light loss of 2 per cent also occurs by reflection at the cornea-air interface. Here we will take $\tau = 1$ and neglect the 2 per cent loss. This should lead to an upper value of the retinal illumination. In any case it will give the energy values considered *at the level of the cornea* before the light enters the eye. The average area of the pupil at very low illuminations may be taken as 0·495 cm² (Le Grand, 1948). The value for L in equation (4) then yields the following value for the mean retinal illumination in radiation of $0\cdot51\mu$ corresponding to the absolute threshold for the 47° field

$$D = 9\cdot09 \times 10^{-8} \text{ erg } (0\cdot51\mu)/\text{sec} \times \text{cm}^2 \text{ (retina)} \quad (6)$$

The area of the retinal image of the field being about 1·47 cm², the corresponding flux of energy for the whole of the retinal image of the 47° field is $1\cdot35 \times 10^{-7}$ erg $(0\cdot51\mu)$/sec.* This is obviously an extremely small value since 1 erg is approximately the energy required to lift one milligram one centimetre.

THE PHYSICAL QUANTUM THEORY

For radiation of wave-length $0\cdot51\mu$ the quantum of energy $h\nu$ ($h = 6\cdot624 \times 10^{-27}$ erg × sec = Planck's constant; $\nu = c/\lambda$ = light frequency, c being the velocity of light) is equal to $3\cdot89 \times 10^{-12}$ erg. Using this quantity as a natural unit of radiant energy we find that the energy flux received by the retinal image of the 47° field at threshold corresponds to 35,000 quanta $(0\cdot51\mu)$ per sec.

This result may be compared to the number of rods contained in the same retinal area, which is roughly twenty million (Østerberg, 1935). This shows that even if, *per impossibile*, all the radiant energy incident on the cornea were absorbed without loss by the retinal rods, the amount of energy absorbed per

* The present calculations are made on the basis of 0·51 instead of $0\cdot507\mu$ which is the actual value of the maximum of the C.I.E. efficiency function, the difference here being insignificant.

second would correspond to only 1 quantum per 500 rods. Now, as is universally known, radiant energy can be absorbed (or emitted) only in single quanta. A quantum is the smallest amount of light that can be absorbed by the retina. It is impossible therefore for a light-quantum here to be 'shared' among several rods.

On this basis the following example shows the high efficiency reached by the rod visual mechanism. Consider a human subject looking for half a minute at the present 47° field with its intensity raised to ten times the absolute threshold luminance. (This is somewhat dimmer than the luminance of a very dark night sky; cf. Part I, p. 13.) The larger number of the rods in the subject's retina will then remain unaffected by the light stimulus for, according to the above figures, they will have failed to absorb even one single quantum during the entire half-minute exposure. Yet at such a luminance, according to Fig. 3 (p. 10), visual acuity is equal to 0·017. This means that a 60′ C can be visually resolved; the angular diameter of such a test object is 5°, which is little more than one-tenth the diameter of the large field. Thus a fair degree of accuracy in the perception of form is here achieved by the visual system even though the light available is so weak that more than half the retinal receptors must remain entirely unstimulated by it.

In the above connexion it may be emphasized that quantum properties are in evidence only in the case of absorption or emission of radiation by matter. In the flux of radiant energy entering the eye, for instance, individual quanta cannot be localized. They become localized only after radiation has been absorbed, for instance in a rod. The light flux as a whole can be regarded as propagated according to the wave-theory of radiation. This must be borne in mind in referring, say, to a retinal illumination of 'x quanta ($0{\cdot}51\mu$) per sec. per rod'. Such a phrase merely means that the *mean* flux of radiant energy reaching the rod per second is $x \times (3{\cdot}89 \times 10^{-12})$ erg. If then the absorption factor of the rod for this radiation is p, the mean number of quanta absorbed per second per rod is simply px. And since light absorption takes place in individual processes each involving one single quantum and one single molecule (or at any rate one single chromophore group), it follows that the mean number of molecules (or chromophore groups) in the rod which have been excited as a direct result of light absorption will also be px per second. This shows why it is convenient to use the energy of the light quantum $h\nu$ as a unit of radiant energy. Yet it would be incorrect to believe that, prior to absorption, the light flux behaves as a stream of particles. Such a belief would lead to completely erroneous conclusions regarding phenomena of light diffraction and interference.

Numbers of absorbed quanta, such as px, may be fractional because they are mean numbers; but the actual numbers absorbed are of course always integral numbers. They undergo wide random fluctuations when the (constant) mean number is small (e.g., see Pirenne, 1951, 1956).

Light Quanta Involved in the C *Threshold Experiments*

Table 8 gives the results of Fig. 17 (p. 44) recalculated in terms of the equivalent energy E of $\lambda = 0{\cdot}51\mu$ received every 0·1 sec. by the retinal image of the gap of the Landolt C test objects, the energy being expressed in light-quantum units. The table includes the value $E = D \times 1{\cdot}47 \times 0{\cdot}1$ for the retinal image of the 47° field, D being given by equation (6); it also includes the value for the 'flash threshold' calculated not for 0·1 sec. but for the actual duration of the flash, 0·2 sec.

TABLE 8

Calculation of the number of light-quanta involved in the experiments of Part I

	3° circular field (0·2 sec. flash)	47° circular field	295′ C	191′ C	96′ C	24′ C	12′ C	6′ C	3′ C
		(continuous exposure)							
Width of gap in C, or diameter of field (mins. of arc) ..	180	2,820	295	191	96	24	12	6	3
Mean log (threshold luminance in cd/m²)	$\bar{3}$·074	$\bar{7}$·875	$\bar{6}$·174	$\bar{6}$·284	$\bar{6}$·581	$\bar{3}$·526	$\bar{4}$·245	$\bar{3}$·451	$\bar{2}$·094
Mean pupil area (cm²)	0·495	0·495	0·495	0·495	0·492	0·482	0·468	0·420	0·377
Mean energy E received by the eye in 0·1 sec. from the gap in the C or the 47° field or in 0·2 sec. from the 3° field (number of quanta, 0·51μ) ..	450 (0·2 sec.)	3,500	97	52	26	14	18	65	64

The minimum light flux necessary for human vision, that is, the flux entering the eye when a subject looks at a light source of small angular dimensions just bright enough to be seen under the most favourable conditions of observation, has an average value corresponding roughly to 800 quanta (0·51μ) per second; some workers have reported values as low as 200 quanta per second (Pirenne, 1956). Bearing in mind the different time unit used in Table 8, namely 0·1 sec. instead of 1·0 sec., it is seen that the fluxes E corresponding to the C test objects are of the same order of magnitude as the minimum light flux necessary for vision.

The calculations take into account the variations of the average pupil area with field luminance according to the approximation given by Le Grand (1948). At the lower luminance levels used in these experiments, pupil contraction is negligible, while at the highest levels, corresponding to acuity $\frac{1}{3}$, it only amounts to a decrease of 0·12 log unit (or 32 per cent) in area. A series of experiments (flash threshold, C thresholds up to acuity $\frac{1}{3}$) was made on Subject 11—who had the lowest flash-threshold value among the subjects of Part I—before and after instillation of paredrine hydrobromide in the eyes; there was no significant difference between the two series of measurements. It seems likely that paredrine was ineffective in producing a significant increase in pupil area in these experiments and thus led to no decrease in the threshold values.

The actual size of the pupil was not measured in the subjects of the experiments and it is not impossible that the mean pupil area of our young subjects was greater than the average values somewhat arbitrarily chosen for the calculations. On the other hand we have seen that the amounts of 0·51μ energy here taken to be equivalent to white light may be slightly too high. Again, the estimate of 0·1 sec. for the effective duration of a fixation pause is somewhat arbitrary.

In spite of such uncertainties, Table 8 clearly shows that the true values of E for the C test objects must represent very small amounts of light. The lowest value given in the table is 14 quanta, for the 24′ C. The actual energy reaching the retina will be less than this on account of losses in the eye media, the transmission factor τ being smaller than unity. According to Ludvigh and McCarthy (1938), $\tau = 0{\cdot}5$ for $\lambda = 0{\cdot}51\mu$. Further, only a fraction, f, of the energy incident on the retina is absorbed by the rods. According to recent experiments by Rushton (1956), the probable value of f is 0·2 for $\lambda = 0{\cdot}51\mu$. We may therefore take 0·1 as the value of the product $(\tau \times f)$ which represents the fraction of the light incident on the cornea which becomes absorbed in the retinal rods (Pirenne, 1956). We then find 1·4 quanta as the mean number of quanta absorbed per 0·1 sec. in the retinal image of the bright gap in the 24′ C; this is only a mean value. In particular, on account of physical fluctuations the actual (integral) number of quanta absorbed by the rods is bound to undergo wide variations from one elementary exposure to another.

Eye movements: probability effect. In each trial, since the test object was exposed for several seconds, the subject's eyes were able to take a large number of 'snapshots', each one corresponding to a fixation pause (Appendix A, p. 55). Even though the mean number of quanta absorbed in one such exposure may have been very low, the actual number may have been much higher than the mean in one or a few of the many elementary exposures occurring during one trial. As a result, the subject may have seen the gap of the C only in the particular 'snapshots' corresponding to these successful fixation pauses. The same argument would of course apply in the simpler case of the absolute threshold of a small light-source (Pirenne, 1948).

A simplified numerical example may be considered in this connexion. Assume that a mean of 1·4 quanta per 0·1 sec. is absorbed by the rods. The probability of seeing in any 0·1 sec. is then 0·000622 if 7 quanta are required. The probability of seeing in 15 sec. considered as 150 independent exposures is then 0·09. This value is very sensitive to variations in the number of quanta required and the mean number of quanta. For instance, if only 6 are required, the probability becomes 0·38, or if the mean becomes 1·8, it becomes 0·32. In view of the possible inaccuracies mentioned above (p. 48), the estimate of the number of quanta seems of the right order.

The numbers 6 and 7 have been used in this example because special measurements of the absolute threshold using fixation and flash have shown that they are of the order of magnitude of the minimum number of quanta which must act upon the retina in order to produce a sensation of light (Hecht, Shlaer and Pirenne, 1942). It is generally accepted that the value of this number lies in a range of from 2 to about 20 quanta for rod vision (Pirenne, 1956).

It will be remembered that the threshold luminance in the experiments of Part I corresponded to a frequency of seeing of about three in four, so that in about one in four trials at this intensity no successful fixation pause would have occurred. Again, since the experiments were made using both eyes, it might have been sufficient for one eye only to have made a successful fixation pause to enable the subject to report correctly the position of the C. Besides the unavoidable physical fluctuations of the light stimulus, biological variations of sensitivity may also have taken place; for instance, it is likely that the sensitivity varies from one to another among the retinal regions involved in the different elementary exposures; further, there are marked variations in the actual duration of the fixation pauses, which were all taken as having an effective duration of

0·1 sec. On account of these complications it is not possible to calculate th exact number of quanta which must be absorbed by the rods in one elementar exposure in order to enable the subject to see the gap in the Landolt ring (no even to calculate the exact number of quanta which must enter the eye in orde to do so). It seems, however, that the part of the retina directly concerned i this visual act can respond to the absorption of a few quanta only.

Thus the relevant parts of the visual system, far from working at supralimina levels of intensity, are reacting to quantities of light of the same order as th minimum amount necessary for vision; and this amount is not much large than the ultimate natural limit of sensitivity, which would correspond to th absorption of one single light quantum by the retina. It must be pointed out however, that absorption of a single light quantum by one rod is not sufficien to cause a visual sensation—although it is sufficient to stimulate the rod. Thi can be demonstrated on the basis of different arguments relating to simpl absolute threshold experiments (cf. Pirenne, 1951, 1956).

The physical and physiological limits of efficiency. The values of E for the othe C test objects in Table 8, although larger than for the 24′ C, lead to simila conclusions. In all these acuity experiments the eye is making effective use o amounts of light close to the amount corresponding to the absolute threshold a determined under the best experimental conditions. This may in part explai why to many subjects such experiments appeared difficult and tiring, much mor so than the present measurement of the 'flash threshold'. From a physiologica and physical standpoint, the acuity measurements in the range studied here ar possibly equivalent to absolute threshold measurements of a very particula kind. Since they involve eye movements, they are much more complex thar threshold measurements made with the fixation-and-flash method.

The performance of the present subjects was not very far from reaching the absolute limit set by the very nature of light; accordingly, it may be concluded that their performance must have come near to, or reached, the physiologica limit of their visual system, and that they had reached a high degree of training

It should be pointed out here that it might be possible to explain the presen acuity experiments on a more complicated basis involving the intervention of the off-fibres found in the vertebrate retina by Hartline (1938, 1940). Such an explanation would not be essentially different from the above, unless th absolute threshold of the off-fibres were lower in terms of continuous illumination than that of the ordinary fibres receiving the image of the bright gap in the C. In such a case the black broken ring might be 'seen' through the intermediary of off-fibres while the image of the bright gap itself would fail to stimulate the retina.*

Light Quanta Involved in the Flash Threshold Experiments

The amount of radiant energy of $\lambda = 0{\cdot}51\mu$ measured at the cornea, which is equivalent to the quantity of light corresponding to the mean 'flash threshold' of the twenty-two subjects of Part I, can be readily calculated (Table 8, p. 48). Its mean value is 450 light-quanta. As has already been pointed out, this valu is higher than that corresponding to the gaps in the C test objects. In particula it is about 0·7 log unit higher than the amount of energy which would be involved per 0·2 sec. in the detection of a C having a gap of 180′, that is, o

* *Note added in proof*: Some experiments (Pirenne, 1957) suggest that this theory may be the correct one, at least under certain conditions. If so, however, the general conclusions reached here would hardly be affected.

similar size to the 3° field itself. If the flash had lasted 0·1 instead of 0·2 sec. it can be calculated that a difference of about 0·5 log unit would persist. It is probable that this difference can be largly accounted for by the probability considerations discussed in the previous section (p. 49). Moreover, the retinal region used in detecting the gap of the C may not be the same as the region, 7° from the fovea, used for the flash. Thus the apparent discrepancy can be explained on the basis of differences in experimental conditions.

From the above measurements of the flash threshold it is possible to obtain by extrapolation an estimate of the mean energy content for the same subjects of a flash of 10′ diameter and 0·001 sec. duration, which conditions should lead to a minimal value of the absolute threshold. On the basis of the results of Graham and Margaria (1935), which, however, refer to 15° instead of 7° eccentricity, such an extrapolation can be made; it leads to a value of about 50 quanta. This very rough estimate is in reasonable agreement with the values ranging from 54 to 148 quanta which were measured directly on specially trained subjects, using a 10′ field and a 0·001 sec. exposure at a position 20° from the fovea (Hecht, Shlaer and Pirenne, 1942). It is this investigation which led to a value of the order of 6 for the retinal threshold.

While at first sight the equivalence between white light and green light of 0·51μ used as a basis for the above calculations of numbers of quanta might appear to be a somewhat artificial device, this is not so from a theoretical point of view. According to the now generally accepted theory of rod vision, what determines the visual effectiveness of light on the dark-adapted rods is the number of quanta absorbed by rhodopsin, the visual pigment present in the rods. The scotopic relative luminous efficiency of radiation can be satisfactorily accounted for on the basis of the absorption spectrum of rhodopsin. Therefore, although scotopically equivalent amounts of white and 0·51μ light contain very different numbers of quanta, the (mean) number of quanta actually absorbed in the rods is the same in both cases. The action of the two different lights on the rod cells—that is, the most peripheral elements of the rod visual system—is also the same in both cases. Since the fraction of light absorbed in the rods is not known with certainty, it is often more convenient to deal with scotopically equivalent amounts of lights determined at the level of the cornea, rather than with the actual amounts absorbed by the rods.

THE RELATIONSHIP BETWEEN ACUITY AND THE ABSOLUTE THRESHOLD

The preceding considerations show that a close relationship may be expected to exist between the absolute threshold and scotopic visual acuity, since in both cases the amounts of energy involved are so very small, even in terms of light quanta.

In the present experiments, however, eye movements tend to complicate the situation. It is in acuity experiments made in a constant retinal region (with the help of a fixation point) that the relationship between acuity and threshold should become clearest. Experiments made using black disks as test objects (Pirenne, 1946, 1953) showed a close relationship between retinal sensitivity and acuity at levels near the absolute threshold. Other experiments made on Service personnel using the same conditions of fixation and flash for both threshold and form vision have shown a high correlation between these two functions (S. Hecht, 1943, private communication). Accounts of more recent experiments of the same kind have been published by Ogilvie, Ryan, Cowan and Querengesser (1955), who measured the absolute light threshold and the threshold luminance

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of two types of acuity at two levels, in 25 subjects, and found that the absolute light threshold was a significant predictor of the threshold luminance of acuity.

Morris and Dimmick (1950) have also described experiments on scotopic acuity made using a fixation point. Although their experimental conditions were very different from the present ones, their results confirm the existence of correlations between acuities at different scotopic luminance levels. They did not, however, measure the absolute thresholds of their subjects, and their measurements did not extend below an acuity value of about 0·025.

The results given in this Report may be explained theoretically in the following way. Assume that, in any given retinal region, at scotopic luminance levels, there is for all subjects the same definite relationship between sensitivity and accuracy of form perception. From subject to subject there may be differences due to differences in pupil area, in the transmission factor of the eye media, in the proportion of light absorbed by the retinal rods, or in the number of absorbed quanta required for threshold stimulation, etc.; the combined result of such differences is the filter factor. This factor will then affect equally the sensitivity and the accuracy of the retinal region under consideration; theoretically there will be a perfect correlation between threshold sensitivity and form vision.

Now make the further assumption that, except for the filter factor, all eyes are built and function in the same way; that the filter factor is the same for all relevant parts of one given retina, that in the normal use of the eyes the subject always uses the region giving optimum acuity under the experimental conditions, and that psychological conditions of attention, etc. are the same in all the subjects. Then it is clear that the filter factor theory will be true and that there will be a perfect theoretical correlation between the flash threshold and form perception at low illuminations.

The results of Parts I, II and IV are here taken as evidence that this 'filter factor' theory is approximately correct for the groups of trained subjects who were studied. As stated above, detailed studies of the functioning of the retina under controlled conditions also support the theory. These studies, as yet incomplete, seem to open up a promising field, particularly when full attention is given to the quantum properties of light in connexion with the problems involved.

Summary

1. In the experiments described in Parts I and II of this Report, the luminance levels required to resolve black Landolt rings of different sizes were measured on a number of young adult subjects, and correlated with their absolute thresholds measured by means of the fixation-and-flash method. Significant correlations were found for all luminance levels for which scotopic vision is used in resolving the Landolt rings.

2. The range of uncertain seeing is considerable in all the experiments (cf. § 8 below). The effect of these experimental errors on the correlations is discussed. It is such that the correlations will appear to be much reduced under certain circumstances. This may explain why some other workers failed to obtain significant correlations between different night-vision tests.

3. In Part III, the 'filter factor' theory is discussed. According to this theory, the eyes of different subjects are similar as regards scotopic vision in all respects, except that one subject may require k times as much light as another to perform any visual task. It is shown that the experimental results of Parts I and II are in agreement with this theory, at least as a good approximation.

4. Further experiments carried out to test the 'filter factor' theory are described in Part IV. Perceptual efficiency was here measured by the score given for a description of a complicated picture viewed at low illumination. It was found that, after training, the score obtained at a standard illumination was closely related to the value of the flash absolute threshold. Further, if the illumination was increased by varying amounts to compensate for differences in the flash thresholds of different subjects, it was found that, as predicted by the 'filter factor' theory, all subjects had similar scores.

5. In Part V, the results of the experiments of Parts I and II are discussed from the point of view of the quantum theory. It is shown that the amounts of light absorbed by the retina during the flash of the flash threshold measurements, and absorbed from the gaps in the Landolt rings during fixation pauses, are of the same order of magnitude, and consist of only a few light quanta. It is concluded that the two tasks have a certain similarity, and that, in performing them, the subjects had come very close to the physiological limits of their visual ability.

6. Appendix A consists of a discussion of the fixation-and-flash method of measuring absolute visual thresholds. The advantages of the method over methods involving continuous fixation and methods in which no fixation is used are demonstrated. Its reliability is confirmed by the reproducibility of measurements of the course of dark adaptation obtained by the fixation-and-flash technique.

7. The method of obtaining the absolute energy values given in Part V is explained in Appendix B. Details are given of the calculation of the spectral energy distribution of the light reaching the subject, and the effect of a colour filter on the distribution. The method of calibrating the neutral wedges is described.

8. A hitherto unpublished war-time report by Hartline and McDonald is included as Appendix C of the Report. It discusses the method of carrying out simple tests of visual efficiency at low illuminations. Formulae are given for scoring such tests and for estimating the accuracy of the scores. The methods described in this Appendix were used in the experiments of Part II of the Report.

APPENDIX A

The Fixation-and-Flash Method of Threshold Measurement

The method of fixation and flash for threshold measurements will be discussed here on account of its importance for the present experiments. This method is now generally used in visual research when physiological conditions must be kept under strict control.

When a given point of the visual field attracts our attention and we fix our gaze on it, our eye moves until the retinal image of the point falls into the fovea centralis; this constitutes the fixation reflex. Under such conditions the eyeball cannot rotate around its axis. Thus, each time the human subject whose flash threshold is being measured brings his gaze on to the fixation point, his eye and retina assume a fixed reproducible position with regard to the external visual field, provided of course that the position of his head is unchanged. The accuracy of such repeated fixation is of the order of 5′ of arc (Barlow, 1952). Within such limits of accuracy, therefore, the geometrical image of the test field will fall each time on the same part of the retina. This is important because in general the sensitivity of the retina varies greatly with the position of the test field. In some circumstances the retinal position of the image of a test field may be of greater importance than its size. Thus, while a large field centrally fixated has a lower threshold than a small field similarly fixated, this is an effect of retinal position rather than an effect of size. Hecht, Haig and Wald (1935), for instance, showed that a 2° field viewed 10° laterally has almost as low a threshold as a 20° field viewed centrally. The image of the large field reaches peripheral regions of the retina which are more sensitive than the central region corresponding to the small field. The importance of the retinal position of the test field has again been confirmed in recent experiments by Pirenne and Marriott (1954).

An angle of 7° from the fixation point was used in all the present experiments. This position had been found convenient in previous studies of dark adaptation (Hecht and Shlaer, 1938; Hecht and Mandelbaum, 1939). It gives a peripheral measurement without making it necessary for the subject to look for the test field too far 'out of the corner of his eye'. Although, according to Østerberg (1935), the maximum number of rods—about 150,000 rods per mm^2—is found about 20° from the fovea, the retinal region corresponding to an eccentricity of 7° already contains a large number of them—about 100,000 per mm^2 (cf. graphs of Østerberg's results replotted in Pirenne, 1948). In the present Report all flash thresholds were measured with a test field placed 7° below the fixation point on the vertical meridian except for some special experiments (see p. 57) when the field was placed 7° temporally on the horizontal meridian (cf. Fig. 1A, p. 57). The retina is not exactly symmetrical in its properties around the fovea, but the differences between the horizontal and vertical will not affect the present argument.

When the intensity of the red fixation point is not much brighter than is necessary for comfort, the presence of this ancillary light source placed 7° from the test field is without influence on the value of the threshold, as can be readily calculated (Pirenne and Denton, 1951) using the equation derived by Stiles and Crawford (1937) from their extensive experimental studies on the effects of glare.

The size of the field, 3° in diameter, was the same as that used by Hecht and Shlaer (1938) and Hecht and Mandelbaum (1939). It will be noted that its

angular diameter, 180′, is large enough to make the effect of ordinary errors of fixation almost negligible, since these are of the order of 5′.

The duration of the flash, 0·2 sec., was also the same as that used by Hecht and his co-workers. For a 3° field in the periphery, according to Graham and Margaria (1935), the relation between duration and threshold luminance is a simple reciprocal one only up to a duration of about 0·001 sec.; that is, for such short duration the product (duration × threshold luminance) is constant except for the statistical variations due to the uncertainty of seeing. For durations greater than 0·001 sec. this product, which is of course equal to the total (mean) amount of light contained in the light flash, increases steadily until it tends to become constant and independent of the duration, but this only occurs for durations of more than one second. Theoretically such long exposures have the advantage that the threshold luminance becomes independent of the actual exposure time and, therefore, of inaccuracies of the shutter, but in practice they are not convenient, mainly because one can hardly be sure that the subject maintains accurate fixation during the exposure. A 0·2 sec. exposure is more convenient to use, for while it does not offer the above theoretical advantage, it is still long enough to reduce appreciably the effect of possible inaccuracies of the shutter. The results plotted by Graham and Margaria (1935) show that an increase of 1 per cent in the duration here decreases the threshold luminance by only about 0·4 per cent—whereas in the case of a 0·001 sec. duration it would of course decrease it by 1 per cent.

When an untrained subject, having fixed his gaze on the fixation point, sees, or thinks he sees, a flash of light illuminating the peripheral test field, he may tend to turn his gaze in the direction of the field as a result of the fixation reflex. Now the reaction time for the required movement of the eyes is of the order of 0·2 sec., so that the 0·2 sec. flash may be over by the time the subject begins to shift his gaze. Whereas such a loss of fixation will be of little importance for an exposure of this duration, this would not be true in the case of longer exposure times.

SACCADIC EYE MOVEMENTS

Far from being an artificial technique bearing no relation to the usual working of the eye, it would appear that the fixation-and-flash method may in fact reproduce under physiologically precise conditions the very manner in which the retina is stimulated in ordinary life. For on account of the saccadic movements of the eyeballs which, in the ordinary use of the eyes, occur several times per second, our retina is subjected to discontinuous stimulation even when we look at a steady source of light (Woodworth, 1939). The retina thus takes 'snapshots' of the light source. The exposure time of each 'snapshot' is equal to the duration of the corresponding fixation pause between two eye movements; this generally varies between 0·1 and 0·3 sec. (Barlow, 1952).

In connexion with the use of light flashes, it will have been noted in the section on experimental methods (p. 5) that the subject was required to keep fixation each time a flash was presented, but not in between the presentations. Keeping accurate fixation for any length of time is very difficult. Helmholtz (1896) wrote that eye movements are so natural to us that it entails extraordinary effort and attention to fix our gaze even for ten or twenty seconds quite accurately on a definite point of the visual field, and that, as soon as we succeed in doing so, unusual phenomena take place. In particular, it is well known (Aubert, 1865) that if strict fixation is maintained when the dark-adapted eye looks at a dim

source of light, the subject soon stops seeing this light altogether. This was once more verified in the following experiments.

Adaptation to a Constant Retinal Illumination

Experiments were made on one subject using a field 5° in diameter placed 20° nasally to the fixation point (green light, Ilford filter 604; 2 mm. artificial pupil). It was found that when the subject kept his gaze fixed on the red fixation point he ceased to see the test field between 5 and 10 seconds after the light had been switched on to the field. The whole visual field then became uniformly dark, except for the fixation point. When the light illuminating the test field was switched off, however, the subject detected a marked change, the test field re-appearing momentarily as a dark object, subjectively darker than the surrounding 'darkness'; this is probably due to the excitation of 'off fibres' in the optic nerve (Hartline, 1938, 1940).*

The time required for the test field to become subjectively invisible was of the order of 5–10 seconds for field luminances near absolute threshold or higher, up to 1,000 times the absolute threshold. Since the bleaching of rhodopsin must be negligible even at the higher intensities used (Denton and Pirenne, 1954a), and since the time of disappearance varied but little with intensity, it is likely that the phenomenon is due to processes occurring in the nervous connexions of the retina or in the visual pathways, which make themselves felt after a fairly constant time of a few seconds, independently of the strength of stimulation at the receptor level.

EXPERIMENTS ON THE REPRODUCIBILITY OF THE COURSE OF DARK ADAPTATION

As mentioned at the end of Part IV, the reproducibility of the course of dark adaptation as determined by the fixation-and-flash method has a bearing on the reliability of this method, which was extensively used here as a measurement of sensory efficiency. Experiments made under conditions as similar as possible to those used by Hecht and his collaborators confirmed the high degree of reproducibility, from subject to subject, of their method.

The use of violet light was introduced by Hecht in the study of dark adaptation for clinical or dietary investigations, because it greatly helps to emphasize the features of the curve describing the course of dark adaptation. When experiments are made under the conditions prescribed by Hecht and Shlaer (1938), including the conditions for the light adaptation which must precede the dark adaptation measurements, a clearer separation of the cone and rod curves is obtained with violet light than is generally the case with white light. This is due to the great difference of sensitivity between rods and cones for light of short wavelength. Again, during the period corresponding to the cone part of the dark adaptation curve, the subject sees the test field as a violet circle, while during the subsequent period of rod adaptation it looks to him generally greyish or colourless—to the extent that some of the subjects come to think that the experimenter has actually replaced the violet test light by a white light in the course of the measurements. This change in colour helps to define more precisely the cone-rod transition time. For normal subjects this characteristic time is fairly constant (6 to 10 min. using Hecht and Shlaer's particular conditions).

* Similar observations have been reported by Asher (1956), who also suggests that the effect is mediated by the "off" discharge (cf. footnote, p. 50).

but in certain pathological cases (Hecht and Mandelbaum, 1939), and in vitamin A deprivation (Hume and Krebs, 1949) it may increase considerably.

Method. The measurement of the course of dark adaptation according to the method of Hecht and his co-workers was repeated using a modification of the apparatus described in Part I (p. 1), that is, in order to obtain a sufficiently bright test field a small piece of opal glass was placed in front of the wedges, close to the light source L (Fig. 1, p. 2). A violet filter was placed in front of this field, which was placed at such a distance from the subject that it subtended 3° at his eye. This field replaced the large screen 0 used in Parts I and II.

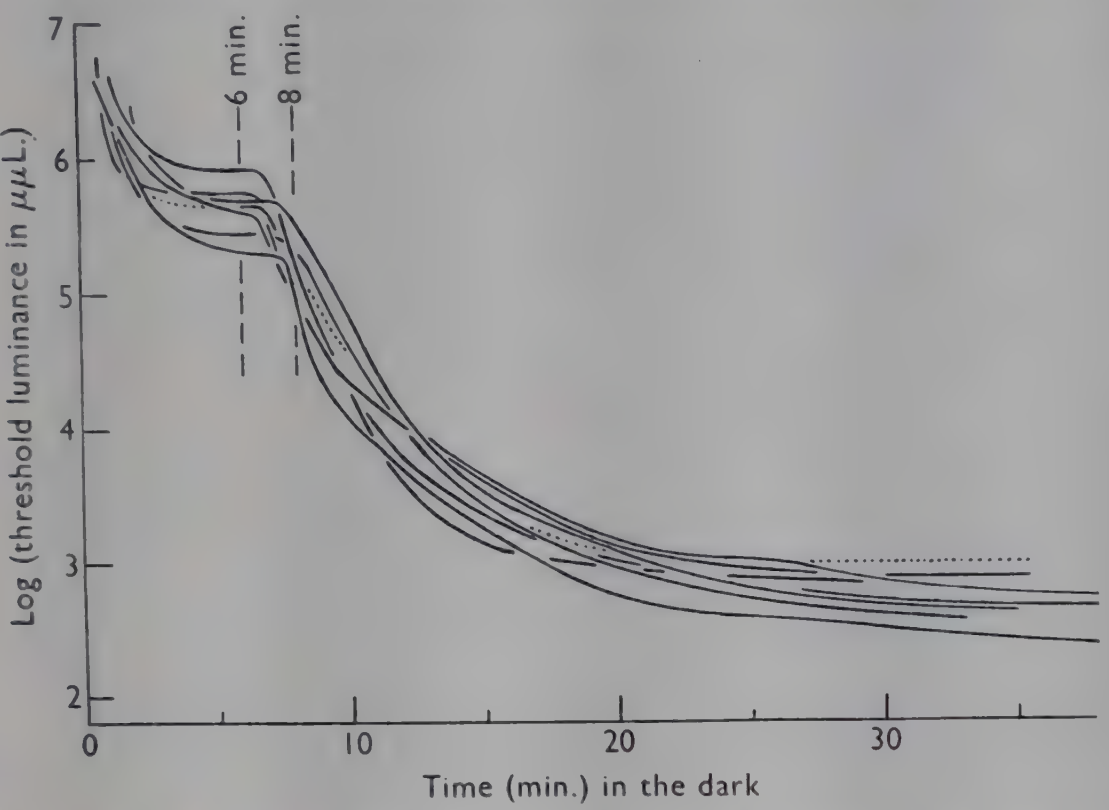

FIG. 1A. The course of dark adaptation in 8 subjects, measured by the Hecht and Shlaer (1938) method. The values of the log luminance scale are based on the data given in Fig. 2A (p. 58) and on the photopic curve adopted by the Commission Internationale de l'Eclairage in 1924 (as explained on p. 65). The figure is not intended to show each of the curves separately, but rather to indicate that they are all similar in shape.

The experimental conditions, which were the same as those used by Hecht and Shlaer (1938), were as follows:

The subject was light-adapted by looking for three minutes at a circular white field of luminance 1,500 millilamberts. (This bright field was obtained using a Maxwellian view system (Walsh, 1953) similar to that described by Hecht and Shlaer (1938), in which the light source was the surface of an opal electric bulb; the same principle was used in the arrangement shown in Fig. 2B (p. 68). The image of the extended source, focused on to the subject's eye, was much larger than the pupil of the eye, so that the position of the pupil was not critical. Contrary to what seems to be sometimes believed, such an arrangement is very convenient for use even with inexperienced subjects.) The diameter of this field was 35°, and a fixation mark was used so that its centre fell approximately 7° from the fovea. Both light-adapting field and test field were viewed 7° temporally (in the visual field), using the right eye with natural pupil. After three minutes the large light-adapting field was switched off and replaced by the 3° test field, which was lit by the experimenter in 0·2 sec. flashes with violet light. The subject

kept his gaze on a red fixation point each time he was being presented with such a flash. Thus the conditions were similar to those for the fixation-and-flash measurements described in Part I (Fig. 2*b*, p. 3), except that the test field was placed temporally to instead of under the fixation point, and violet instead of white light was used.

The threshold for the test stimulus was estimated rapidly at various times after the end of light adaptation. The results obtained for eight subjects are reproduced in Fig. 1A; the dotted line represents the results for Subject N (see p. 57), who gave a curve of usual type except for a high final threshold value. After half an hour, when the threshold had become almost constant, more accurate threshold measurements were made using the method of Hartline and McDonald (Appendix C, p. 70). The accuracy of these measurements is discussed below (p. 60).

Results. The measurements given in Fig. 1A constitute an independent verification of Hecht's results, since they were made in a different laboratory, with different apparatus and different subjects. The general course of dark adaptation is the same as that found by Hecht and Mandelbaum (1939). In particular, the rod-cone transition time varies between 6 and 8 min. in the subjects studied, in agreement with the range of 6 to 10 min. observed by Hecht and Mandelbaum for 110 subjects.

In Fig. 1A the absolute luminance values for the whole curve, including the final threshold, after about half-an-hour's dark adaptation, are generally lower than the values obtained by Hecht and Mandelbaum (1939); but this is certainly due to a different method of defining the luminance of the test field. (This also applies to the values given in Figs. 3A and 4A, pp. 60 and 61.) The luminance in micromicrolamberts ($\mu\mu$L) was calculated on the basis of (*a*) the luminance of the test field in white light, (*b*) the colour temperature, that is, the relative spectral energy distribution of this light, (*c*) the spectral transmission of the violet-glass filter, Corning No. 511, as shown in Fig. 2A, and (*d*) the photopic

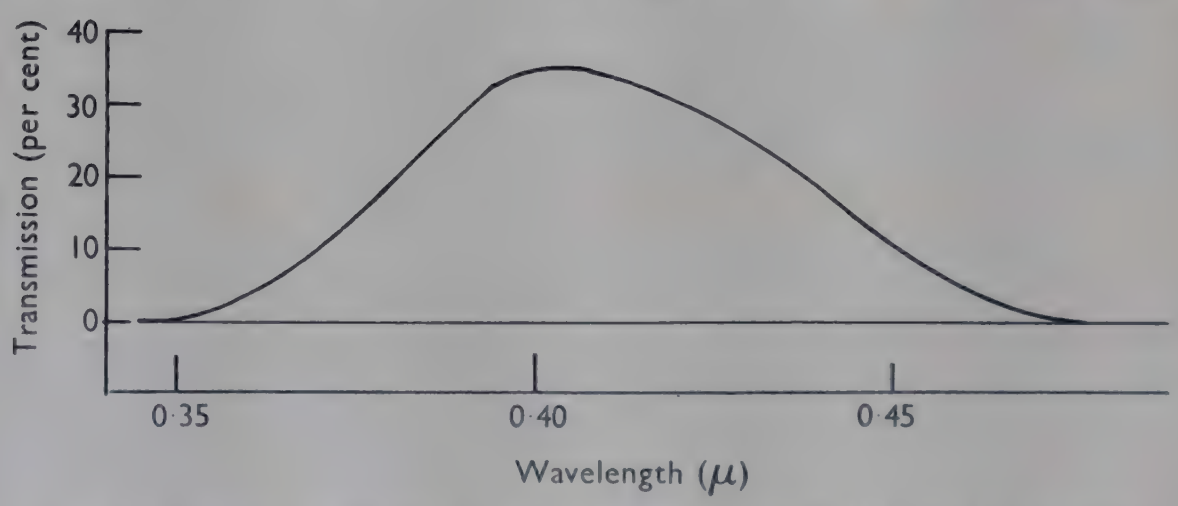

FIG. 2A. Spectral transmission of the violet filter, Corning 511, used in the experiments on the course of dark adaptation (Fig. 1A). In the visible range this filter does not transmit wave-lengths greater than 0·48μ.

(relative) luminous efficiency of radiation, V_λ, adopted in 1924 by the Commission Internationale de l'Eclairage (Walsh, 1953). In the case of Hecht and Shlaer's measurements, on the other hand, the luminance was measured by visual photometry using a heterochromatic matching method. It is known that the 1924 C.I.E. photopic luminous efficiency curve is probably in error at the extreme blue end of the spectrum and this explains the discrepancy.

Measurements made by visual heterochromatic photometry in the present case led to luminance values 0·8 log unit higher. The results then are in general agreement with Hecht's results, but a perfect check is not possible because different eyes were used both in the photometric calibrations and in the dark adaptation measurements. While the problem of the absolute calibration of coloured light sources is notoriously difficult, this has little effect on the results discussed in the present Report, for in the case of measurements with violet light comparison was made only between relative values obtained with one given apparatus.

The luminance scale of the Hecht-Shlaer portable adaptometer Model 3 had been determined using the above method of calculation and was therefore based on the 1924 C.I.E. photopic function. Final absolute thresholds measured on the same subjects using the present apparatus (calibrated on the basis of the C.I.E. function) and the Hecht-Shlaer adaptometer Model 3 were about 0·1 log unit higher on the latter instrument. This small difference is explained by the fact that the colour filter in the H.S. adaptometer is not Corning 511 but a filter combination giving a narrower spectral band at somewhat longer wavelengths. Thus there is no discrepancy between absolute luminance values when the different instruments are calibrated in the same manner.

Comparison with Other Investigations. The results shown in Fig. 1A thus confirm the reproducibility of the main features of the course of dark adaptation measured by the fixation-and-flash method of Hecht and Shlaer. Reproducibility of results in one and the same subject only proves that the subject performed the experiment each time in the same way, but the present results indicate that the different subjects were all being tested under similar physiological conditions. The results are in marked contrast to the large individual differences in the shape of the curve and in the rod-cone transition time observed from subject to subject in certain other methods where no fixation point is used (Yudkin, Robertson and Yudkin, 1943) or where fixation and a continuously exposed field are used (Craik and Vernon, 1942). This probably helps to explain why no correlation between absolute sensitivity and perceptual efficiency was observed by Craik and Vernon (1942) who used the latter method for measuring the sensitivity; but reference must be made to the different characteristics, discussed in Part IV (p. 41), of the perceptual tests used by these workers compared with those used in the present experiments.

Finally it may be mentioned that Mandelbaum (1941), using the Hecht-Shlaer method, found that strychnine, amphetamine, caffeine, phenobarbital and morphine in pharmacologic doses all failed to influence significantly the course of dark adaptation. (In the case of alcohol (180 ml. taken orally) the whole adaptation curve was shifted upwards to a higher intensity level by 0·3 log unit, the effect being similar to that of oxygen deprivation.) The negative results relating to the influence of drugs are at variance with those reported by other workers who used different methods for measuring dark adaptation and who reported that strychnine, for instance, had a marked effect on the course of dark adaptation and on the final threshold. Thus Mandelbaum's results again suggest that the fixation-and-flash method does keep under control certain variable factors which in other methods may affect the threshold measurements in unpredictable ways.

VIOLET LIGHT VERSUS WHITE LIGHT

In the experiments of Parts I and II, the flash threshold was measured by a method very similar to that used by Hecht in the above-mentioned studies of dark

adaptation, except that white instead of violet light was used. It seemed ad- able to use the same white light as that used in the acuity experiments, in or to reduce the possibility of additional variations between subjects. It will noted that the same light source and apparatus were used in these experime for measuring flash threshold and visibility threshold, and this should also h helped to reduce accidental variations in the experiments.

In the experiments of Part IV, however, the flash threshold and the percept efficiency were measured using two different instruments, and the flash thresh was measured using violet light (Hecht-Shlaer adaptometer) while the ot measurements were made with white light. These differences could only te to decrease any existing relationships between sensory and perceptual efficie in Part IV, so that they cannot weaken the conclusions reached there. I Hecht-Shlaer portable adaptometer was used in Part IV partly for practi reasons. If these investigations were to be pursued further, however, it mig be advisable to use the same kind of light, the same light source, etc., in all t tests, as was done in Parts I and II.

ACCURACY OF THE MEASUREMENT OF THE FINAL FLASH THRESHOLD

Figs. 3A and 4A represent measurements of flash thresholds made after ha an-hour's dark adaptation using the scoring method proposed by Hartline a McDonald (Appendix C, p. 70). The experimental conditions were the same those described above (p. 57). In Fig. 3A block diagrams are given of the measu ments of three subjects, P, Y, and N, the subject with the highest thresho

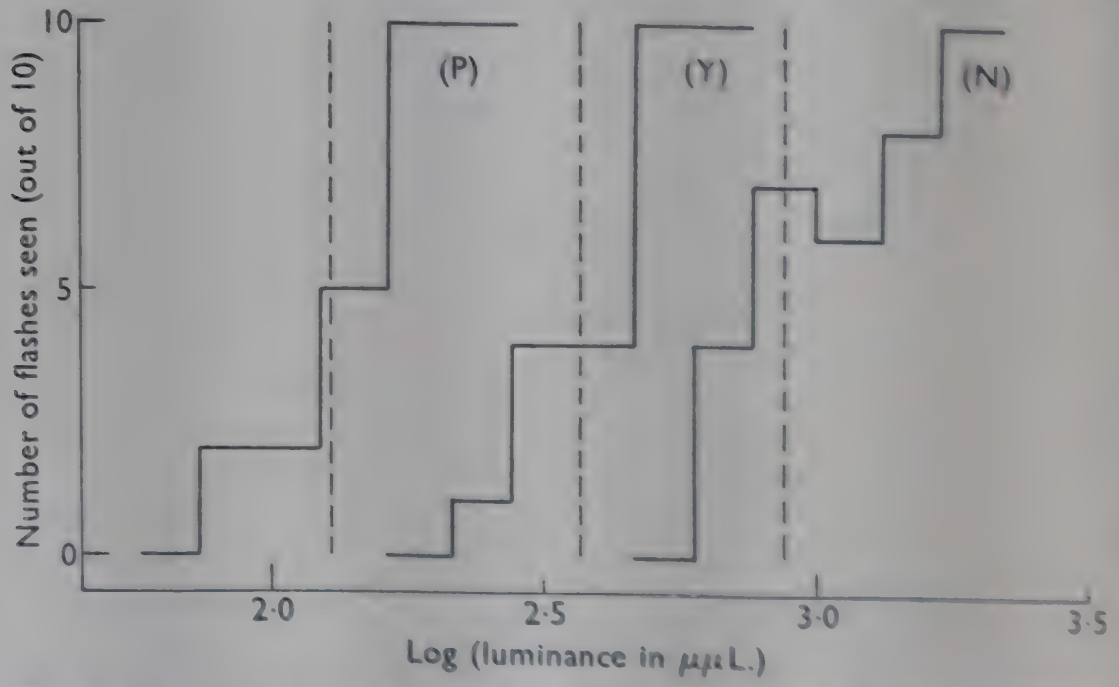

FIG. 3A. Determination of the flash threshold in 3 subjects, P, Y and N, according to the method of Hartline and McDonald. The vertical broken line gives the mean threshold L_m for each subject. The luminance scale is calculated in the same way as in Fig. 1A.

being Subject N. The vertical broken line for each subject gives the 'mea threshold' L_m as defined by Hartline and McDonald's method. Fig. 4A giv block diagrams of three similar sets of measurements made on one subject. C In this figure sections (1*a*) and (1*b*) give measurements made in immedia succession on the same day, while section (2) gives measurements made tw

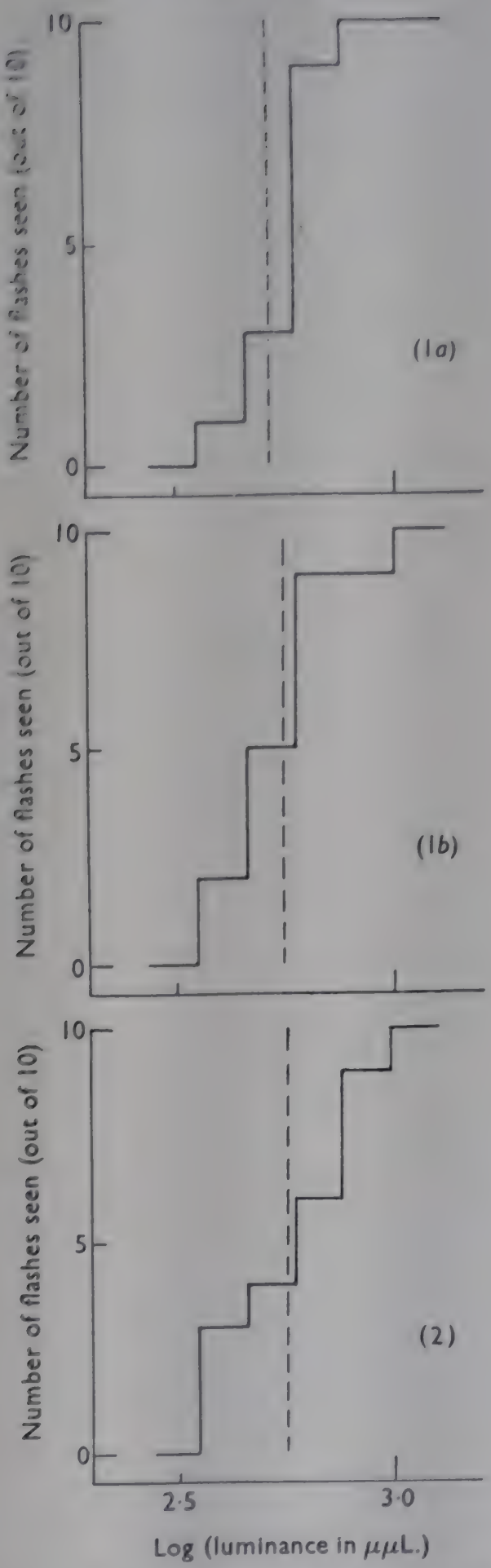

FIG. 4A. Three separate determinations of the flash threshold of 1 subject, C, using the method of Hartline and McDonald. The measurements of Sections 1*a* and 1*b* were taken in immediate succession; those of Section 2 were taken 2 days later. The vertical broken lines give the mean threshold L_m for each determination. The luminance scale is calculated in the same way as in Fig. 1A.

days later. It will be seen that the difference between the two 'mean threshold determined on the same day is of the order of magnitude predicted by Hartlin and McDonald. Also, in this particular case there is very little differenc between the measurements made on the two different days. This is not a invariable occurrence, however. Day-to-day differences of up to 0·3 log uni are often observed in the same subject (Hecht and Mandelbaum, 1939; Hecht Shlaer and Pirenne, 1942; Denton and Pirenne, 1954a). In exceptional case similar differences may even be observed in the course of one day, as shown for instance, on page 16.

APPENDIX B

The Calculation of Radiant Energy Values from Photometric Measurements

The absolute values of radiant energy discussed in Part V were calculated in the following manner.

RELATIVE SPECTRAL ENERGY DISTRIBUTION

The relative emissivity of a tungsten filament lamp run at some given voltage is, for the visible spectrum, almost identical with that of a perfect radiator at some given temperature which is called the 'colour temperature' of the lamp. The emissivity of a perfect radiator is given by Planck's equation. If therefore the colour temperature of the lamp is known, the spectral energy distribution of the light it emits can be calculated, in arbitrary units, from Planck's equation. The values of this function for different temperatures are given in various tables (cf. Walsh, 1953).

Light from the lamp in the apparatus shown in Fig. 1 was photometrically compared with that from a reference lamp calibrated for voltage against colour temperature by the National Physical Laboratory. Light from the apparatus lamp was made to fall upon a magnesium oxide screen and that from the calibrated lamp upon a second similar screen, the two screens being arranged for photometric comparison. The voltage and position of the reference lamp were adjusted until the screens were matched both for colour and luminance. The colour temperatures for the two lamps were now the same and that of the reference lamp could be found from the N.P.L. calibrations.

The lamp of the light source (with neither wedges nor filters in front of it) had a colour temperature of 2440° K. According to measurements made at the National Physical Laboratory, the colour temperature was reduced by about 40° after the light had passed through the opal screen. Thus the colour temperature of the light emitted by the screen was 2400° K.

By viewing the photometric field through colour filters it was ascertained that the relative emissivity of the light-source lamp (opal bulb) could be made to correspond closely to that of the calibrated lamp (clear bulb) over the visible spectral range. Similarly, although it changed its colour temperature, the opal glass of the screen hardly affected the general black-body character of the light passing through it. The relative spectral energy distribution E_λ of the visible light emitted by the opal screen therefore corresponded closely to that of a Planckian radiator of temperature 2400° K. This relative distribution E_λ is shown in Fig. 1B. The arbitrary units in which E_λ is calculated are such that for $\lambda = 0{\cdot}59\mu$, $E_\lambda = 100$ per mμ. It will be noted that E_λ is much larger at the red end than at the violet end of the spectrum, as is generally the case with electric filament lamps.

ABSOLUTE VALUES OF THE SPECTRAL ENERGY DISTRIBUTION

The absolute values of the ordinates of the curve of Fig. 1B could now be obtained on the basis of the luminance of the opal glass screen. With no wedge or filter in front of the lamp of the apparatus of Fig. 1 (p. 2), this luminance was 0·0148 ft.-L., that is, $5{\cdot}06 \times 10^{-6}$ cd/cm^2. This was determined by the

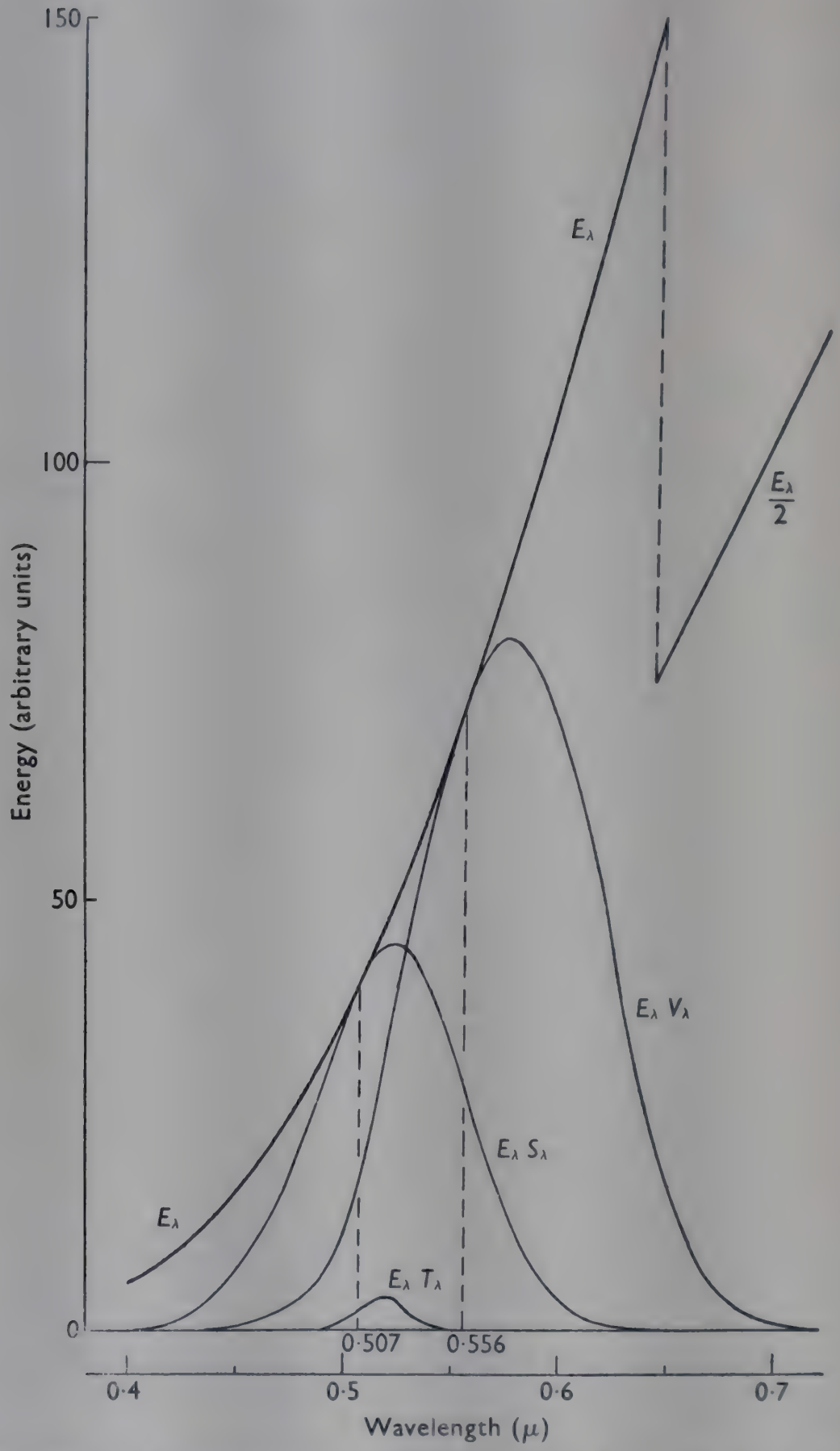

FIG. 1B. E_λ. Relative spectral energy distribution of the light emitted by the opal glass screen used in the experiments of Parts I and II, calculated from Planck's formula for a perfect radiator of temperature 2400° K.

$E_\lambda V_\lambda$. Relative photopic effectiveness of light emitted by the screen at each wavelength. V, the photopic efficiency function, is taken as unity at the maximum, $\lambda = 0{\cdot}556\mu$.

$E_\lambda S_\lambda$. Relative scotopic effectiveness of light emitted by the screen. S, the scotopic efficiency function, is taken as unity at the maximum, $\lambda = 0{\cdot}507\mu$.

$E_\lambda T_\lambda$. Light energy transmitted by a colour filter, Ilford 604, with maximum transmission, about 10 per cent, at about $0{\cdot}52\mu$.

National Physical Laboratory using a physical photometer which gave results independent of the eye of any human observer.

The method used was in effect equivalent to the following theoretical method. First the radiant energy E'_λ emitted by the screen in watts per cm² per unit solid angle (steradian) and per mμ is determined using a physical measuring instrument. Then the relative photopic luminous efficiency function V_λ adopted in 1924 by the Commission Internationale de l'Eclairage is used (V_λ taken as unity at $\lambda = 0{\cdot}556\mu$, the wave-length of maximum photopic sensitivity). The light flux, F, emitted by the screen in lumens/steradian × cm² is calculated (Walsh, 1953) from the equation

$$F = A \int E'_\lambda \, V_\lambda \, d\lambda \tag{7}$$

where A (the reciprocal of the so-called 'mechanical equivalent of light') is equal to 663* lumens/watt (Le Grand, 1948), and the integral is taken over the range of the visible spectrum.

Knowing F and the relative distribution E_λ, the absolute spectral energy distribution, E'_λ, of the light emitted by the opal screen can be calculated on the basis of equation (7). We have

$$E_\lambda = \frac{E'_\lambda}{p} \tag{8}$$

where p is a proportionality factor; to find E'_λ we need only determine p. From equations (7) and (8)

$$p = \frac{F}{A \int E_\lambda \, V_\lambda \, d\lambda} \tag{9}$$

Fig. 1B gives the product $E_\lambda \, V_\lambda$ for 2400° K as a function of λ. The area under this curve represents the integral $\int E_\lambda \, V_\lambda \, d\lambda$. Integrating graphically or by some other means, we find it to be equal to 8550. Now the luminance of the screen in a direction normal to its surface being $5{\cdot}06 \times 10^{-6}$ cd/cm², 1 cm² of screen emitted in this direction a flux of $5{\cdot}06 \times 10^{-6}$ lumen per steradian. For this flux

$$p = \frac{5{\cdot}06 \times 10^{-6}}{663 \times 8550} = 8{\cdot}93 \times 10^{-13} \text{ W/steradian} \times \text{cm}^2 \text{ (field)}$$
$$= 8{\cdot}93 \times 10^{-6} \text{ erg/sec} \times \text{steradian} \times \text{cm}^2 \text{ (field)}. \tag{10}$$

Consider for instance the spectral range from 0·5895 to 0·5905μ, that is, $590 \pm 0{\cdot}5$ mμ. We have seen (p. 63) that $E_{0{\cdot}590\mu} = 100$ per mμ. From equations (8) and (10) it follows that in the above spectral range the screen emitted normally to its surface a flux

$$E' = pE = 8{\cdot}93 \times 10^{-6} \times 100$$
$$= 8{\cdot}93 \times 10^{-4} \text{ erg/sec} \times \text{steradian} \times \text{cm}^2 \text{ (field)}. \tag{11}$$

The preceding calculations show that calibrations of a lamp for both candlepower and colour temperature are in fact equivalent to a calibration of emissivity in energy units. The advantage of the former calibrations is that they are of

* The value of A depends on the values chosen for other physical constants. Walsh (1953) gives $A = 682$.

a type more commonly required for commercial purposes. It will be noted that the above calculations are independent of the characteristics of the vision of actual human observers, for V_λ is here used merely as a mathematical function referring to an imaginary, 'standard', observer.

ENERGY TRANSMITTED BY COLOUR FILTERS

Knowing the spectral distribution E'_λ of the screen illuminated by the lamp of Fig. 1 and the spectral transmission T_λ of a colour filter placed in front of this lamp and isolating a band of the visible spectrum, the energy η now emitted by the screen is given by

$$\eta = \int E'_\lambda \, T_\lambda \, \mathrm{d}\lambda = p \int E_\lambda \, T_\lambda \, \mathrm{d}\lambda. \tag{12}$$

For a particular filter of the type Ilford No. 604, the integral $\int E_\lambda \, T_\lambda \, \mathrm{d}\lambda$, that is, the area under the corresponding curve of Fig. 1B, was equal to 98. When this filter was placed in front of the light source of Fig. 1 therefore, the energy emitted by the opal screen (optical wedges moved out) was

$$\eta = p \times 98 = 8{\cdot}75 \times 10^{-4} \text{ erg/sec} \times \text{steradian} \times \text{cm}^2 \text{ (field)}. \tag{13}$$

When the colour filter isolates a narrow band of the visible spectrum, as in the above example, this arrangement provides a convenient source of radiation which is sufficiently monochromatic for many purposes in visual research, and which is calibrated in absolute energy units. Since the integrals cover only the spectral range visible to man, the calculations automatically disregard the infra-red radiation transmitted by many colour filters. This is often an advantage since infra-red is relatively ineffective visually; yet the fact must be borne in mind. Certain 'cut-off' filters may be used in a similar way, but their use calls for greater precautions (Denton and Pirenne, 1954a, 1954b).

When the luminance of the opal screen is cut down by setting the 'neutral' wedges in a given position, the above value of η must of course be multiplied by the transmission value of the wedges for this setting and for the spectral band used. Thus if, for instance, the optical density of the wedges is 3, η must be multiplied by 1/1000.

RADIATION OF 0·507μ EQUIVALENT TO WHITE LIGHT FOR ROD VISION

The preceding calculations give the spectral distribution of the light emitted by the screen in absolute energy units. We now use the relative scotopic luminous efficiency of radiation S_λ adopted by the Commission Internationale de l'Eclairage (1951). This function is taken as unity at its maximal value, $\lambda = 0{\cdot}507\mu$. The integral

$$Q(0{\cdot}507\mu) = \int E'_\lambda \, S_\lambda \, \mathrm{d}\lambda \tag{14}$$

then gives the amount of radiation of 0·507μ which in scotopic, rod, vision is equivalent to the white light of spectral distribution E'_λ.

According to equations (8) and (9),

$$Q(0{\cdot}507\mu) = \frac{F \int E_\lambda \, S_\lambda \, \mathrm{d}\lambda}{A \int E_\lambda \, V_\lambda \, \mathrm{d}\lambda} = \frac{F}{A} \times R, \quad \text{say.} \tag{15}$$

The integral $\int E_\lambda S_\lambda \, d\lambda$ is the area under the corresponding curve of Fig. 1B. For 2400° K it is equal to 3930 and $R = 0{\cdot}46$. Thus for the present conditions (luminance $= 5{\cdot}06 \times 10^{-6}$ cd/cm^2)

$$Q(0{\cdot}507\mu) = \frac{5{\cdot}06 \times 10^{-6}}{663} \times 0{\cdot}46 \times 10^7$$
$$= 3{\cdot}51 \times 10^{-2} \text{ erg/sec} \times \text{steradian} \times \text{cm}^2 \text{ (field)}. \qquad (16)$$

The fraction R is called the scotopic/photopic ratio of the light of relative spectral distribution E_λ. This ratio has to be used in the calculations because we calculate a scotopic effectiveness on the basis of measurements of luminance which are expressed on a photopic scale.

(It may be pointed out that if we wished to calculate photopic effectiveness, equation (15) should be replaced by the simple expression

$$Q(0{\cdot}556\mu) = \frac{F}{A}. \qquad (17)$$

This equation gives the monochromatic flux of wave-length $0{\cdot}556\mu$ which should be as effective on the retinal cones as a given flux F of white light. However, this calculation arbitrarily disregards the difference of colour which exists here between the two lights. In fact the situation is much more complex than in the case of the rods, since there must be several kinds of cones with different spectral sensitivities.)

The quantity $Q(0{\cdot}507\mu)$ can of course be calculated at once for other values of F corresponding to different experimental conditions, for instance to the absolute threshold luminance of the 47° field. For a luminance of 10^{-6} cd/m^2, which is the order of magnitude of this threshold value, the following result, used in Part V, is obtained:

$$Q'(0{\cdot}507\mu) = 6{\cdot}94 \times 10^{-7} \text{ erg/sec} \times \text{steradian} \times \text{cm}^2 \text{ (field)}. \qquad (18)$$

When the wedges are set for a high optical density value, however, the spectral composition of the white light transmitted may be significantly altered because most optical wedges are not exactly neutral. When the spectral transmission of the wedges has been measured, it is possible to correct for this by considering the wedges as colour filters modifying the spectral distribution E'_λ in a known manner.

The wedges of the apparatus of Fig. 1 transmitted the red end of the visible spectrum more readily than the blue end. (See Fig. 2, Denton and Pirenne, 1954a.) The error involved in using equation (18), which implies that the wedges are perfectly neutral, is not very large, however. The true energy value should be equal to about 0·8 times the result given by equation (18); that is, the latter result is about 0·1 log unit too high. The error is less for higher luminance values. No correction for this error was applied in Part V of this Report (or in the above-mentioned paper by Denton and Pirenne) for the use of slightly high values was of no disadvantage in these discussions, the aim of which was to prove that the amounts of light involved in single visual acts were very small.

CALIBRATION OF THE WEDGES

A simple method for measuring the optical density of optical wedges may be described here. Since such wedges in general are not exactly neutral, even within the human visible range, they must be calibrated for the spectral bands

transmitted by the colour filters used. The apparatus used is shown diagrammatically in Fig. 2B. The light source L_1 is arranged so that it can be photometrically compared with a comparison source, an opal electric lamp L_2. This lamp L_2 can be varied in brightness both by placing neutral filters in front of it and by altering the voltage at which it is run. Both electric lamps are brought to a focus by a positive lens F upon the pupil of the observer's eye E. The light

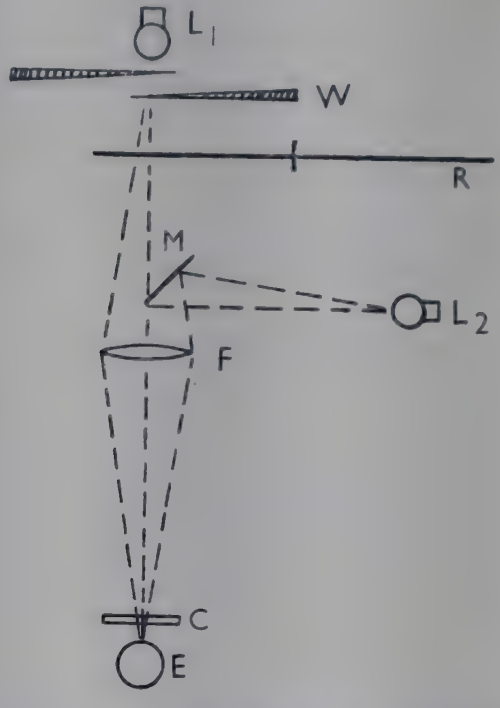

FIG. 2B. Diagram (plan) of the arrangement for calibrating optical wedges by a visual photometric method. L_1 = light source, L_2 = comparison light source, F = lens, M = silvered half of mirror, W = wedges, R = rotating sector, C = colour filter, E = observer's eye.

source L_1 is in the line of view of the observer, the comparison source L_2 is perpendicular to this line of view. A mirror M is arranged at 45° to the two sources, so that the observer's eye E sees the field divided into two halves. The mirror reflects light from the comparison source L_2, while the other half of the field is filled with white light from the light source L_1. The observer thus sees a circular Maxwellian field F divided into two equal parts by a vertical line. In actual fact an ordinary silvered glass mirror is used, from one half of which the silvering has been removed. The vertical line is thus the edge of the silvering on this sheet of glass. In the diagram the transparent part of the glass is not shown, so that M represents the silvered part only.

The calibration of a wedge for the light transmitted by a given colour filter is made in the following stages:

(1) The colour filter C is placed just before the eye so that the light from both sources passes through it. Light from only a restricted band of the spectrum is thus used; differences in colour temperature between the two sources are generally insufficient to make the photometric fields appear different in hue.

(2) With wedges W out, the light from the light source is cut down by a sector R which rotates in front of it at a speed well above the flicker fusion frequency. This rotating sector cuts down the light from the light source in a neutral way to a fraction (say $\frac{1}{10}$) equal to the fraction of time for which the sector transmits light. (Walsh, 1953.) The comparison source L_2 is adjusted until a match is obtained.

(3) The sector R is removed and the match restored by moving 'in' the wedge to be calibrated. The setting of the wedge when the match is restored, which we will call setting (a), is that setting for which the wedge cuts the light from the source to the same fraction as the sector had done previously (if this fraction was $\frac{1}{10}$ the corresponding wedge density is 1).

(4) Starting now with the wedge setting (a), stages (2) and (3) are repeated and the wedge is thus calibrated for settings corresponding to higher optical densities.

Calibration of the wedges for white light is made in the same way but the colour filter is of course omitted. In the study of human rod vision, the use of a narrow spectral band centred near $0{\cdot}5\mu$ is more satisfactory than that of white light, notably because in the former case the wedges are much more nearly neutral. For accurate work the selective transmission of the wedges may introduce errors when white light is used, since, as has been explained, it leads to a change in the relative spectral composition of the light transmitted. On the other hand the use of a narrow-band colour filter has the disadvantage that it decreases the effective light intensity available for the experiments.

CONCLUSION

The above method of calibration rests on visual measurements made by human observers (colour temperature measurement, wedge calibration). In this connexion it may be pointed out that in visual photometric comparisons the high sensitivity of the eye makes it easy to obtain reliable matches at low luminance levels where physical receptors may be difficult to use. For two lights having the same spectral composition, a visual match, of course, corresponds to equal amounts of radiant energy, independently of the spectral sensitivity of the observer.

In 1903 Ångström determined with a bolometer the spectral energy distribution of the light emitted by the Hefner standard lamp. He pointed out that this measurement made it possible to determine visually, with an accuracy sufficient for many purposes, the absolute amounts of radiant energy emitted by other sources in various parts of the visible range. This is essentially the principle of the methods of calibration described here. It may be added that in many cases measurements of radiant energy made with a physical receptor such as a thermopile are not genuine absolute measurements, for they depend upon comparison with a standard source used to calibrate the physical receptor in terms of radiant energy—a thermopile, however, has the great advantage of being a spectrally neutral detector of radiation. Further details on the above method will be found in two papers by Denton and Pirenne (1954a, 1954b).

APPENDIX C

The Frequency of Seeing at Low Illumination

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[*This report, prepared in* 1943 *for the United States' Committee on Aviation Medicine, is reproduced here because of its significance for the present study. It is presented without revision except that minor alterations have been made to bring it into line with the main text, and two footnotes have been added. There is a comment on the report on p.* 79, *and a list of the symbols used is provided at the end* (*p.* 81).]

ABSTRACT

The uncertainty of seeing which characterizes vision at low illumination governs the accuracy with which an individual's night vision can be measured. We have studied this uncertainty of seeing for five simple visual tests:

1. Seeing a flash of light.
2. Distinguishing the orientation of a bright letter T subtending 3° at the eye.
3. Same for a black 3° T (in a 6° field).
4. Same for a grey 3° T (32 per cent contrast).
5. Same for a black 1° T.

At intensities near an individual's threshold (for each particular test) these test objects are sometimes seen and sometimes not, the frequency of seeing varying with the intensity. Using 11 subjects in 50 experiments we measured the frequencies of seeing (corrected for guessing) at various intensities above and below the 'mean threshold' for each experiment, which enabled us to obtain an average frequency-of-seeing curve for each test. If a specified number of trials is made at each of a series of intensity steps covering the entire range of uncertain seeing, it is possible to use a simple arithmetical method for computing the 'mean threshold', which is justified theoretically and which lends itself to scoring a routine or semi-automatic test. This mean so defined has the property that as many trials are 'seen' at intensities below the mean as are 'not seen' at intensities above it. Since the frequency-of-seeing curves are nearly symmetrical, the mean coincides approximately with the intensity of 50 per cent seeing. For a given routine of test procedure the standard error of the 'mean threshold' can be computed from the frequency-of-seeing curve for each test. This makes it possible to design test routines to yield whatever accuracy of measurement may be required.

INTRODUCTION

Vision at low illuminations is characteristically uncertain. Even under carefully controlled laboratory conditions, faintly illuminated objects are sometimes seen, sometimes not. Any test of the night visual capacities of personnel must therefore be designed to take into account this uncertainty, in order that the test should have the degree of precision required for its purpose.

The fact that a visual threshold is not sharply defined is usually ascribed to fluctuations of the observer's ability to see. However, Hecht, Shlaer and Pirenne

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(1942), and Hecht (1942), have recently shown that the minimum amount of energy that can be detected by the eye comprises only a few quanta of light. At such low intensities no light source is perfectly steady, for the number of quanta it emits fluctuates statistically, from moment to moment, about a mean value. The number of quanta absorbed by the visual cells of the retina also fluctuates statistically about a mean value. Even at very low mean intensities it may happen occasionally that enough quanta are absorbed by the retina to elicit a visual sensation; likewise higher intensities may occasionally be missed. Hecht *et al.* (1942) have shown that the probability that a faint light will be seen increases with its mean intensity in a characteristic manner which can be accounted for on the statistical basis of such purely physical fluctuations. In addition to this purely physical fluctuation there may be a certain amount of fluctuation due to the observer.

Whatever the explanation, it is an experimental fact that the frequency with which a light is seen—or any other visual observation is made correctly—out of a given number of trials, varies with the intensity of the light. Fig. 1C, section A, shows the results of an experiment (similar to those reported by Hecht *et al.*, 1942) in which flashes of light of various intensities were observed by a subject. The different intensities were presented in random order until ten flashes had been given at each intensity. The abscissa gives, on a logarithmic scale, the intensities of the flashes. The ordinate gives the number of times out of ten that the flashes were seen at each intensity. At the lowest intensity none of the flashes was reported; at the brightest all ten were seen. Intermediate intensities were sometimes seen, sometimes not, with a 'frequency of seeing' which increased with increasing intensity. It is to be noted that the range of intensities within which seeing is uncertain covers nearly half a log unit, which explains why the determination of a visual threshold, no matter how it is made, must be obtained from the average of many repeated trials if sufficient accuracy is to be obtained.

This type of uncertainty is not confined to the simple test of the absolute threshold by a short flash of light which is reported seen or not seen. Fig. 1C, section B, shows the same kind of frequency-of-seeing curve obtained when the subject is required to report correctly the orientation of a large form (a bright letter T, subtending 3°, exposed for 5 seconds). While the curve is somewhat steeper than that of Fig. 1C, section A, there is still a considerable range of intensities at which the object is sometimes seen correctly, sometimes not. Similar uncertainty of seeing exists at high levels of intensity, and has been measured and fully discussed by Lythgoe (1932) in his study of visual acuity.

The object of obtaining data on the frequency of seeing for any particular visual task is to enable one to specify a procedure for evaluating a 'mean threshold' for that task with a required degree of accuracy. For this purpose we have obtained frequency-of-seeing curves for five different visual tasks using a small group of 11 normal healthy male subjects for observers. The average curves so obtained (Fig. 2C) may be taken as fairly representative of the frequency of seeing by normal subjects for these particular visual tasks.

THE EXPERIMENTS

The tasks which we employed are the following (subjects completely dark adapted):

(a) Fig. 2C, section A. Threshold for light [called 'flash threshold' in the main Report]. A circular patch of light subtending a visual angle of 3°, located 9° below a small red fixation light, was exposed for $\frac{1}{5}$ sec. The screen on which the

light was projected was 1 metre from the subject's eye, and was viewed binocularly. The clicks of the shutter were audible, and the flashes came regularly at 6-second intervals, so that the subjects knew when to expect each flash. The subjects reported simply whether or not they saw a light, and their response to each was recorded. After every 10 flashes, or more often if the subject requested,

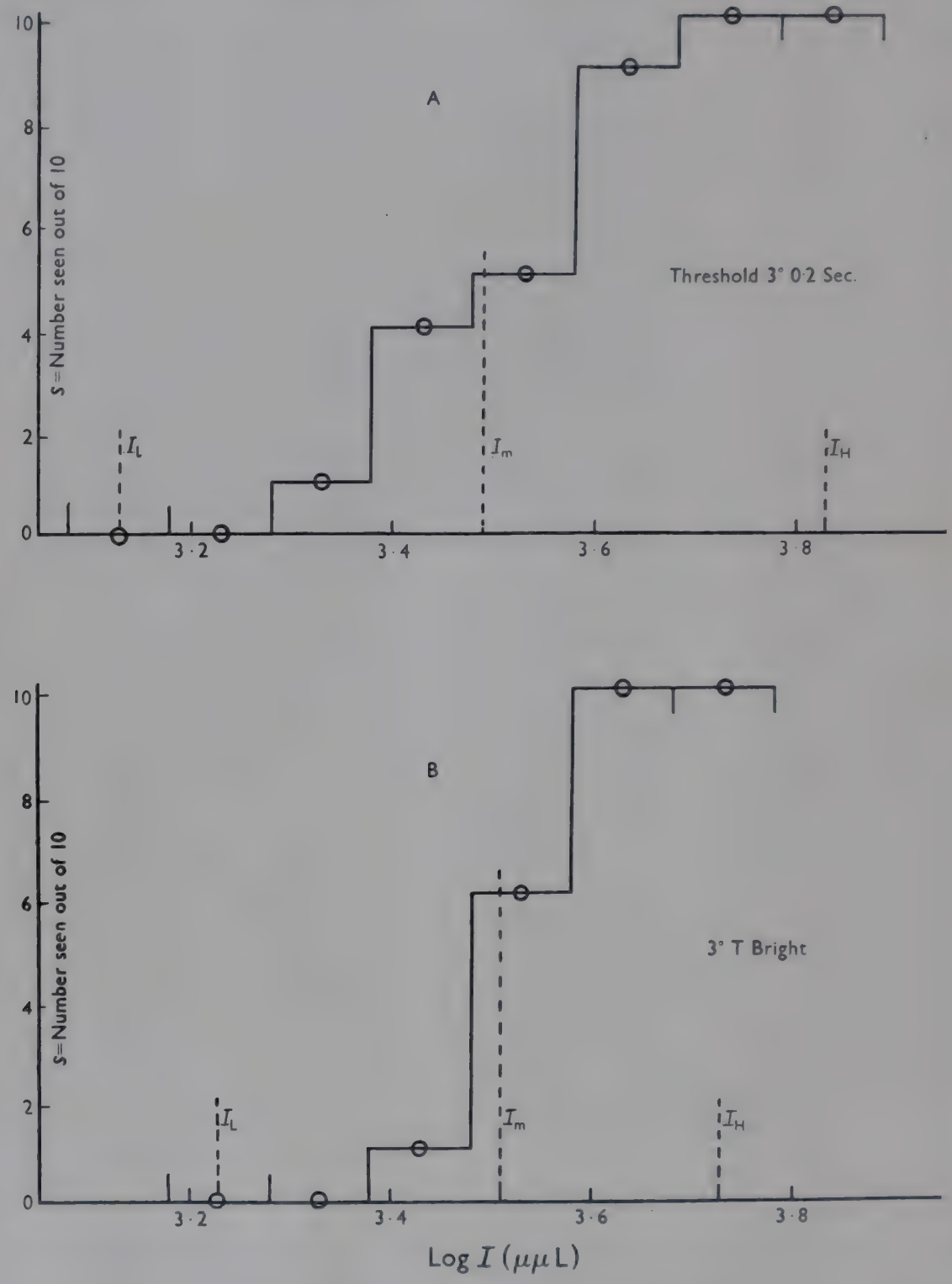

FIG. 1C

a brief rest period was allowed. If for any reason the subject was not prepared for the flash (lack of fixation, blinking, distracting noises) he reported it as missed, and it was not recorded. In addition to the flashes, a number of 'blank' presentations were always given by inserting, unknown to the subject, an opaque shutter into the beam of light. Flashes of different intensities (including the 'blanks') were given in random order. The intensity range covered approximately 0·6 or 0·7

log unit in steps of 0·1 log unit. The highest intensity I_H was one which was invariably seen by the subject, the lowest, I_L, was one which was never seen. In each day's experiment a subject was given a total of 5 presentations at each of the 6 or 7 intensities; in addition, a total of 10 to 20 blanks were interposed. (The smooth curve drawn through the points is derived from a theoretical Poisson distribution and gives the probability of obtaining 7 or more quanta of light for flashes of various average energy contents. This is in good agreement with the experiments of Hecht *et al.*, 1942.)

(b) Fig. 2C, section B. Threshold for large forms (bright). A patch of light in the form of a letter T, subtending 3° (width of stroke 3/5°), was presented for 5 seconds at 15-second intervals in different orientations. Four orientations (T, ⊣, ⊢, ⊥) were used, given at random, and the subjects' reports were recorded as correct, incorrect, or 'Don't know'. Each subject was instructed to use his peripheral vision, and to make a guess if he had any idea at all as to the orientation of the letter, but he was not required to guess wildly. As with the threshold, the entire range of intensities from invariably-correct seeing to no seeing was covered in steps of 0·1 log unit, and 5 presentations at each intensity were given in each day's experiment. (No attempt has been made to fit a theoretical curve to these or the following data.)

(c) Fig. 2C, section C. Threshold for large forms (silhouette). A black letter T, subtending 3°, silhouetted against a circular patch of light subtending 6°. Presentation and recording as with the bright T.

(d) Fig. 2C, section D. Threshold for small forms (silhouette). A black letter T, subtending 1° in a circular patch of light subtending 6°. Presentation and recording as above.

(e) Fig. 2C, section E. Threshold for large forms of low contrast. A 'grey' letter T, 32 per cent contrast, subtending 3° in a circular patch of light subtending 6°. Presentation and recording as above. The exasperating quality of this test object is reflected in the irregular curve; it is clearly not well suited for furnishing a reliable test under the particular conditions of our experiment. The curious shape may in part be explained by a 'rivalry' between the use of central and peripheral vision by the observer.

For each of these tests, four to six experiments were performed, on different days, on each of our 11 subjects. In addition, we have less extensive data on 4°, 2° and ½° black letter T, and on the same sizes of black letter C (Landolt broken ring).

Different individuals require different ranges of intensity in order to perform the same visual task, and each individual varies in his performance from day to day. It is of course the ultimate object of the tests to measure these variations, but for the immediate purpose we wish to lump all the data on each task to provide 'standard' frequency-of-seeing curves. Our data show that for a given task these variations affect principally the location of the curves along the horizontal axis, and that the shape of the curve does not differ appreciably from one experiment to another if we adhere to the logarithmic plot of intensity. (One possible explanation of this is that the differences between individuals are not so much due to differences in the number of quanta required to excite the retina, as in the light losses in the eye, and in the percentage absorption of the light by the retina.) We therefore feel justified in displacing all curves of individual experiments to a common mean, and averaging the frequencies of seeing at the various intensities above and below this mean. The exact method was to calculate for each experiment the 'mean threshold' by the method to be

described below. The number of presentations seen at the various intensities above and below this mean (in 0·1 log unit steps) was then tabulated and summed for all the experiments, and the average frequency of seeing was calculated for each intensity (approximately 250 observations for each point) and plotted in the curves of Fig. 2C.

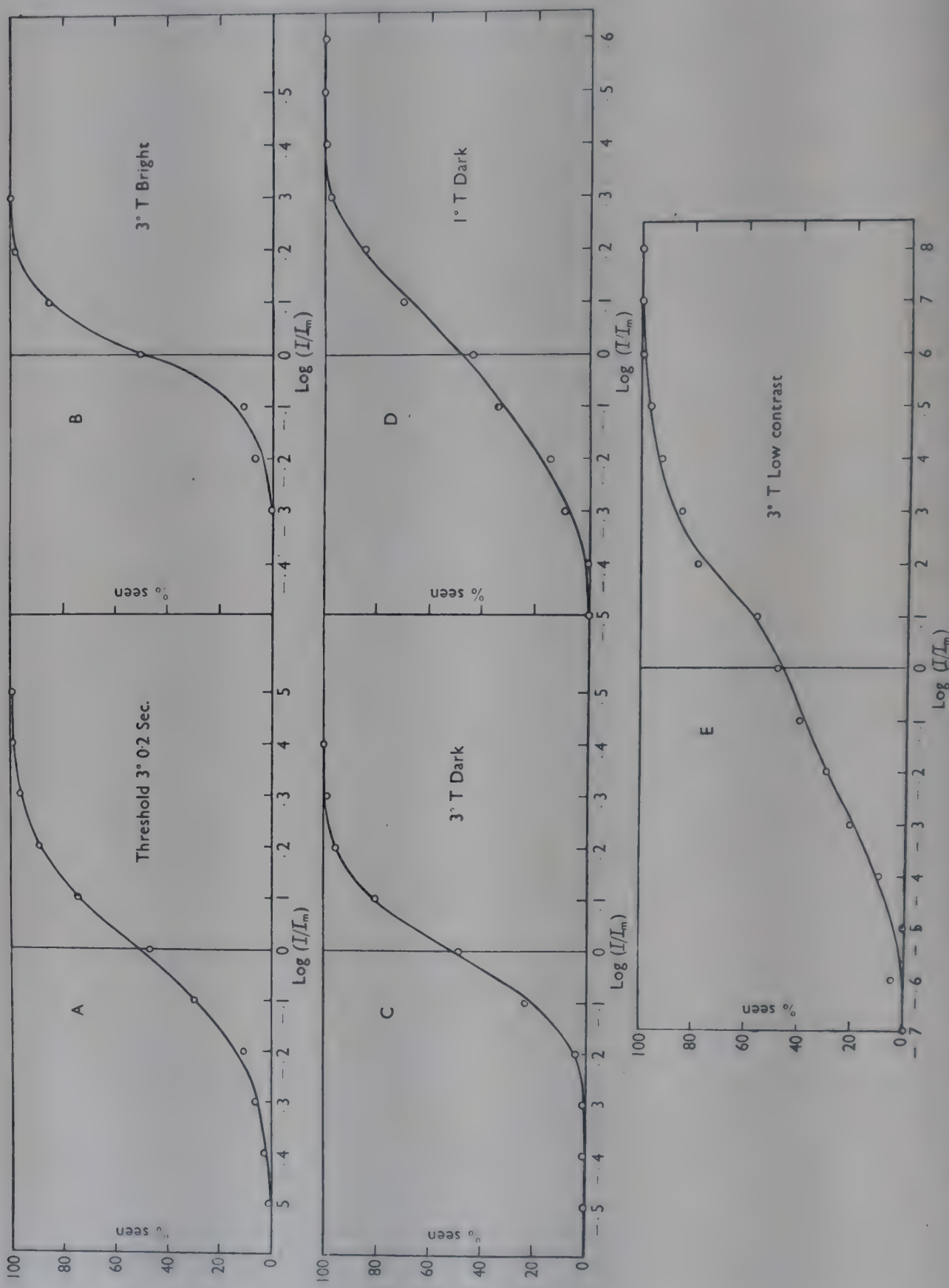

FIG 2C

Correction for Guessing

When the letters were used as test objects, presentations that could not be seen were usually reported 'Don't know'. Occasionally, however, they were

reported, but with their orientations incorrectly given. We have taken into account those incorrect reports on the assumption that they are the result of guess-work. If some of the presentations which are 'really' not seen are guessed at, some of the guesses will be correct by chance, and it is necessary to subtract those lucky guesses from the number of correct reports to get the number 'really' seen. In these experiments we used four possible orientations; guess-work will therefore yield, on the average, one correct report to every three incorrect. The incorrect reports may therefore be taken as a measure of the amount of guess-work and used to estimate the number of guesses that were 'correct by chance'. For every three incorrect reports we have therefore subtracted one from the number of correct reports, to give the number 'really seen' at each intensity of presentation. It is this number that is used to calculate the frequency of seeing at each intensity.

To show experimentally that these assumptions are justified, at least to some extent, we performed the following experiment. A subject (HKH) was tested with the 3° T (dark); those presentations in which he could not distinguish the orientation of the letter to his satisfaction he reported, as usual, 'Don't know', but then he added a guess. A total of 104 reports were thus designated as guesses, and of these 31 were correct. This is only slightly more than the chance expectation, and the frequency-of-seeing curve, corrected for wrong reports, was the same whether the results of 'forced guessing' were included or whether the 'Don't know' reports were recorded as 'not seen' in the usual manner. 'Forced guessing' is somewhat exasperating to the subject, but it may be desirable to adopt it for routine testing, for it tends to force the subject to use his visual ability to its utmost (cf. Lythgoe, 1932).

Correction for Blanks Reported 'Seen'

Even in the simple test of light threshold, where reports are merely 'yes' or 'no' ('seen' or 'not seen'), it is sometimes necessary to take into account something akin to guess-work. Normal subjects, under proper conditions of experimentation, very rarely make the mistake of reporting a 'blank' (shutter click with no light getting through to the observer) as 'seen'. In our subjects, out of a total of 1,200 blanks, only 14 were so reported. This proportion is entirely negligible. We have found, however, that certain abnormal experimental conditions (administration of a drug) resulted, in some subjects, in a marked increase in the number of these 'spurious' reports. (As high as 10–20 per cent of the blanks were reported as 'seen' in several cases.) Therefore, any abnormal procedure which is being tested for its effect on visual threshold must include an adequate number of 'blanks', and computations of frequency of seeing and of mean thresholds must take into account this 'spurious' seeing if it ceases to be insignificant. Allowance may be made for such 'guess-work' by applying the same principle used in allowing for incorrect reports of the orientation of a test letter. In this case, however, the frequency of 'spurious' seeing of the flashes must be inferred from its incidence among the blanks. Thus if 10 per cent of the blanks are reported 'seen', we may reason that, on the average, for every nine flashes reported 'not seen' one was reported 'seen' spuriously (i.e. would have been reported 'seen' even if no light had been allowed through). This may be somewhat arbitrary, but it is probably the best that can be done where the subjects' performance is badly impaired.

A SIMPLE METHOD OF ESTIMATING THE 'MEAN THRESHOLD'

The purpose of any test is to measure an individual's 'mean threshold' for a particular visual task. This can do no more than determine, with a prescribed accuracy, the position of his frequency-of-seeing curve on the intensity scale. This can be done satisfactorily in any of several ways, provided that some pre-determined routine is followed. We can recommend the method of giving a specified number of exposures at various fixed intensities covering the entire range of uncertain seeing as we have used it here, to measure frequency of seeing. This method lends itself well to routine tests by unskilled technician assistants, and to automatic testing machines. The number of exposures, and the intensities used, will depend upon the required accuracy, the basic form of frequency-of-seeing curve for the particular test, and the criterion used to estimate the 'mean threshold'.

Various criteria for estimating a 'mean threshold' might be applied to the results of each individual test. A Poisson sum could be fitted to the data, where that is appropriate; Bliss's Probit method may be used for data like this; more simply, the intensity required to yield a specified frequency of seeing (e.g. 50 per cent) may be estimated graphically. We have chosen an even simpler arithmetical method. Imagine that a smooth curve similar to that of Fig. 2C, section A, has been drawn through the data of Fig. 1C, section A, representing the relation between log I and s, the number of presentations seen in n presentations. The mean abscissa of this curve, log I_m, measured from any arbitrary intensity I_0 is given by:

$$\frac{\int_0^n (\log I - \log I_0)\, ds}{\int_0^n ds} = \log I_m - \log I_0 \qquad (19)$$

The denominator of this expression is n. The numerator is the area between the curve and a perpendicular erected at the ordinate I_0. For the unsmoothed data this area is given by forming the sum of the products of the intensity interval $\Delta(\log I)$ times s, the number of presentations seen at each intensity (or the number unseen, $u = n - s$ depending upon the choice of I_0). For log I_0 one should take either the highest intensity used in the experiment, log I_H, or the lowest, log I_L, but to these must be added or subtracted respectively the quantity $\frac{1}{2}\Delta(\log I)$, since the intensity interval is of finite width.

The sum of the products is either

$$\sum_{I_L}^{I_H} s \times \Delta(\log I) \quad \text{or} \quad \sum_{I_L}^{I_H} u \times \Delta(\log I)$$

and if the intensity intervals on a log scale are all equal, these expressions are simply $S \times \Delta(\log I)$ or $U \times \Delta(\log I)$ respectively, where S is the total number seen in the entire experiment, and U the total number not seen ($U + S = N$ is the total number of presentations given). The formulae for mean log threshold are therefore:

$$\log I_m = \log I_H + \tfrac{1}{2}\Delta(\log I) - \frac{S}{n} \times \Delta(\log I) \qquad (20)$$

or

$$\log I_m = \frac{U}{n} \times \Delta(\log I) + \log I_L - \tfrac{1}{2}\Delta(\log I) \qquad (21)$$

Thus it is only necessary to count the total number of presentations seen (or he total not seen) in a given experiment to obtain a direct measure of the mean hreshold. It is not even necessary to record which presentations are seen.

Correction for Guessing and for Blanks Reported 'Seen'

In computing the numbers 'seen' and 'not seen' it is necessary to make allowances for guess-work. Here again it is only necessary to record the total number of errors, and apply the suitable correction:

$$S = R - \frac{p'}{q'} W \tag{22}$$

$$U = N - S \tag{23}$$

where R = total number right, W = total number wrong, p' = the probability of guessing right, $q' = (1 - p')$ = the probability of guessing wrong. Values of p' and q' are to be taken either from the design of the experiment, as in the case of the oriented letters, or from the experimental data, as in the case of the 'blank' exposures. If 'forced guessing' is used, then the computation is somewhat simplified, since $R + W = N$,

$$U = N - S = N - \left(R - \frac{p'}{q'} W\right) = W\left(1 + \frac{p'}{q'}\right) = \frac{W}{q'} \tag{24}$$

Thus a very simple scoring for a routine test would be to force the guessing, and count the total number of errors. The totals could be used directly as measures of thresholds, without further conversion unless desired for special purposes. Any such experiment requires, of course, a fixed number of presentations at each of a series of fixed intensities. The intensities must be separated by equal intervals (on a log scale) and must cover the range from no seeing in the best individual to perfect seeing in the poorest.

Theoretical Meaning of the 'Mean Threshold' Estimate

The theoretical 'mean threshold' as we have defined it has the property that if equal numbers of presentations were made at closely spaced equal intervals through the range, about the same number of presentations would be 'seen' at intensities below the mean as were 'not seen' above it. If presentations are equally spaced on a linear intensity scale and if an equal number of presentations are seen above as not seen below the 'mean threshold', it is easy to show that the mean so defined yields the 'number (k) of quanta required for seeing' when applied to a Poisson distribution in the case where all the 'filter factors'* are known. A linear intensity scale must thus be used, but a logarithmic one (which must be used if variable 'filter factors' are the principal causes of individual variation) introduces an error which in general is fairly small.† From Fig. 2C (p. 74) it is seen that most of the frequency-of-seeing curves are sufficiently symmetrical for the 'mean threshold' to correspond very nearly to a 50 per cent

* ['Filter factors' is used here in a slightly different sense from that of the main Report and refers to the ratio between the energy measured at the cornea and the energy absorbed by the receptors. This ratio is equal to the product of factors such as the transmission of the eye media and the light absorption by the visual pigment in the receptor cells. (*M.P.*, *F.M.*, and *E.O'D.*)]

† [When a logarithmic scale is used the 'mean threshold' corresponds approximately to $(k - \frac{1}{2})$. The error of this approximation is quite negligible, being about 0·0006 log unit for $k = 6$ and increasing to 0·01 log unit at $k = 2$. This can be shown as follows. If the abscissa is measured on a logarithmic scale, so that $z = \log_e x$ and $dz = dx/x$, m is defined by the equation $\log_e m - \log_e \delta = \int_{\delta}^{\infty} (1 - p)\, dz$, where δ is some small number which will later be

frequency of seeing. Thus our simple method of computing 'mean threshold' seems sound on theoretical grounds as well as convenient from a practical standpoint.

Standard Error of the 'Mean Threshold'

We are now in a position to estimate the error of a given threshold, determined in the way we have just described. It is clear, in the first place, that the intensity interval must be reasonably small, otherwise the summation performed will not approximate an integration sufficiently closely. Otherwise it makes no difference whether many presentations are made at a few intensities, or a few presentations at each of many intensities; this may be decided from practical considerations. For a given experimental routine, the uncertainty of the mean may be estimated by the following considerations. The probability p of seeing a presentation at a specified intensity is given by the appropriate frequency-of-seeing curve in Fig. 2C (p. 74). If a number of trials are made of n presentations each, the numbers seen, s, will have a distribution given by the terms of the binomial expansion of $(p + q)^n$. The mean of this distribution will be $\bar{s} = np$, its standard deviation $\sigma = \sqrt{npq}$. This is true at each intensity. Since the 'mean threshold' is determined by $S = \Sigma s$ (using a single set of n presentations to determine s at each intensity) its standard error will be given by

$$\sigma_m = \frac{\Delta(\log I)}{n} \sqrt{\Sigma npq} \qquad (25)$$

Table 1C gives the value of σ_m corresponding to $n = 1$ and $\Delta(\log I) = 0{\cdot}01$ for the five different tests used. For other values of n, divide by $\sqrt{n}$. For other values of $\Delta(\log I)$, Σpq will be approximately multiplied by $\dfrac{0{\cdot}01}{\Delta(\log I)}$; accordingly, the tabulated values should be multiplied by $\{\Delta(\log I)/0{\cdot}01\}^{\frac{1}{2}}$.

The values of the standard errors given in Table 1C for $\Delta(\log I) = 0{\cdot}01$ and $n = 1$ are the same for $\Delta(\log I) = 0{\cdot}1$ and $n = 10$ (except for a small discrepancy due to non-linearity over an interval as large as 0·1 log unit). In our individual experiments the conditions corresponded to $\Delta(\log I) = 0{\cdot}1$ and $n = 5$; this should lead to standard errors about 40 per cent greater than those given in Table 1C. This calculation agrees with our experience concerning the reliability of the 'mean threshold' judged from repetitions of an experiment at the same sitting.

The tabulated standard errors show the relative accuracies of the different tests when the same number of presentations is made at each intensity. The less steep the frequency-of-seeing-curve for a test, the greater its standard error in

---

assumed to tend to zero. This is equivalent to equation (19) but the range of z is now infinite.

Now $$\int_\delta^\infty (1 - p)\, dz = \int_\delta^\infty \sum_{r=0}^{k-1} \frac{x^{r-1} e^{-x}}{r!}\, dx \simeq \int_\delta^\infty \frac{e^{-x}}{x}\, dx + \sum_1^{k-1} \frac{1}{r}$$

and $$\operatorname*{Lt}_{\delta \to 0} \left\{ \int_\delta^\infty \frac{e^{-x}}{x}\, dx + \log_e \delta \right\} = -\gamma$$

Hence $\log_e m = \sum_1^{k-1} \frac{1}{r} - \gamma = F(k - 1)$, the digamma function of Karl Pearson. But for large k, $F(k - 1) \simeq \log_e(k - \frac{1}{2})$ and this approximation holds quite well even for small values of k. (*F. M.*)]

Table 1C, and the greater will be the number of presentations required at each intensity to yield a specified accuracy. In addition, tests which possess a flat

TABLE 1C

Values of σ_m $(\Delta (\log I) = 0{\cdot}01; n = 1)$ *for five different tests*

'Flash' threshold ..	0·031
3°T (bright)	0·024
3°T (dark)	0·026
3°T (32% contrast) ..	0·041
1°T	0·034

These values are calculated from the results of Fig. 2C according to the formula

$$\frac{0{\cdot}01}{1} \times \sqrt{\Sigma p(1-p)}$$

where p is the ordinate of the frequency-of-seeing curve, p being, of course, equal to 1 for 100 per cent seen.

frequency-of-seeing curve require still more presentations, owing to the larger intensity range that must be covered. Of the five tests reported here, the 3°T (either black or bright) yielded the steepest frequency-of-seeing curves, the low contrast T yielded the flattest. Where the time required for a visual test is of importance, the different numbers of presentations required by different tasks will affect the relative desirabilities of the different tasks.

* * *

[*Comment on Appendix C.* The above method of estimating the threshold is a modification of the psychological 'method of constants' (Myers, 1911). The scoring procedure described is Kärber's method (Finney, 1952) for estimating 50 per cent points in biological assays. This procedure has been subjected to considerable criticism, and certainly it has serious drawbacks when applied to the type of biological data for which it was originally proposed. For the present purpose, however, it seems the best method, since the usual objections to it do not apply, or apply only in a much reduced degree. Since the method (in some cases slightly modified) has been used for many of the experiments described in the main Report, it seems worth while to discuss briefly the criticisms which have been made, and their applicability to the experiments described here.

(a) The most serious objection is that the use of a range of luminances from 'never seen' to 'always seen' does not give a very efficient estimate of the location parameter. On grounds of efficiency, it would be better to take observations only at points close to the 50 per cent point. Other considerations, however, make the method described the most satisfactory for this sort of work.

In the case of the flash threshold, it is desirable to include bright flashes to ensure that the subject remains familar with the position and size of the test field during the whole course of the measurements. The brighter among the flashes, constituting the series used here for estimating the 'mean threshold', automatically fulfil this requirement. Again, the use of both blanks and flashes of very low intensity gives a valuable check on the performance of the subject. For instance, positive responses at low levels (apart from seeing blanks) would suggest that the subject's performance had not reached the physiological limit of his visual system. On the other hand, negative responses at high intensity

levels might indicate fatigue. Thus psychological factors which affect a subject's performance may be revealed only when the full range of the curve is studied.

Further, the reasoning which suggests that intensities close to the 50 per cent point only should be used does not take into consideration the fact that the subject's task is more difficult for certain flashes near the limit of visibility than for flashes which are unhesitatingly reported as 'not seen', and, of course, for flashes sufficiently bright to be unhesitatingly 'seen'. Often illusory 'flashes' are seen with blanks; trained subjects learn to distinguish these appearances as illusions but it is often difficult to decide whether the vague 'presence' which is seen with flashes near the limit of visibility is in fact an illusion. Accordingly a method using observations taken only at intensities close to the 50 per cent point may be quite unreliable for psychological reasons. On account of the subjective complexity of the threshold measurements, systematic errors might occur. Such errors would remain undetected unless the method were modified to include brighter and dimmer flashes—which in turn would lead one back to a method resembling that of Hartline and McDonald.

In the case of the other visual thresholds considered here, arguments of a similar kind would lead to a similar conclusion. The randomization of luminance levels is an important part of the procedure recommended by Hartline and McDonald, particularly in the case of the flash threshold. This, in conjunction with the use of a wide range of levels and the inclusion of blanks, makes the method more or less proof against any subjective effect which may arise if the subject knows the actual intensity of the flash. In the case of the C thresholds randomization of luminance levels is less important because here there is an automatic check on guessing without its being necessary to use blanks.

The method is suggested as a routine test suitable for the rapid testing of large numbers of subjects with widely differing thresholds by semi-skilled operators. For this purpose it is important to have the test as nearly standardized as possible, and this is best achieved by taking observations over a wide range.

(b) A second criticism of Kärber's method is that it leads to biased estimates of the 50 per cent point. It is true that in most cases the response curve is not exactly symmetrical, and that if this is so, the score does not exactly represent the 50 per cent point. But here the scores are used only for comparative purposes, and the 50 per cent point as such has no particular interest. In fact for the flash threshold it is rather the 'number of quanta required for seeing' *where it is appropriate* (see Pirenne, 1951, 1956), which would be the basic parameter, and this often corresponds roughly to the 55 per cent point. As is mentioned on p. 77 the Kärber score does almost represent this parameter.

(c) Thirdly, it is objected that it is difficult to estimate the standard errors of the Kärber scores. Equation (25) gives the standard error correctly, but the estimation of p and q by the method described leads to an underestimate of the standard error. In fact, in the experiments described here, the bias in the standard error is quite negligible. At the worst, when only one observation is taken at each level, there is a maximum bias of $\frac{1}{4}$ in Σpq—estimated, of course, from several sets of observations, on the same or different subjects, all adjusted to the same mean. Thus for the flash threshold with single flashes at intervals of 0·1 log unit, $\Sigma pq = 1$ (from Table 1C) and the standard error might be multiplied by $\sqrt{1{\cdot}25}$, i.e. increased by 12 per cent. With flashes at intervals of 0·01 log unit, $\Sigma pq = 10$ and the standard error might be multiplied by $\sqrt{\frac{10{\cdot}25}{10}}$, i.e. increased

by 1·2 per cent. The effect of taking r flashes at each level is the same as that of dividing the interval by r; the bias in the standard error is also divided by r.

In practice it is not very easy to check the standard error, since this involves several sets of observations on the same subject on the same day and the question of fatigue becomes important. However, Hartline and McDonald found that their calculation agreed with their experience concerning the reliability of the 'mean threshold' tested in this way. Such experiments as we have done (e.g. Fig. 4A, p. 61) are also in satisfactory agreement with the predicted value.

Finally it should be noted that Stiles and Crawford (1934) developed a method for measuring visual differential thresholds, which they called the 'multiple decision method', and that this method which they found very satisfactory in use is essentially the same as the scoring method described by Hartline and McDonald. (*M. P., F. M., and E. O'D.*)]

SYMBOLS USED IN APPENDIX C

Note. Throughout this appendix the intensity, I, refers to the luminance of the test field.

I	'Intensity'—that is, the luminance of the test field.
I_H	The highest luminance used, taken as one which was invariably seen by the subject.
I_L	The lowest luminance used, taken as one which was never seen by the subject.
I_m	The threshold luminance; log I_m is the mean abscissa of the curve relating log I and s, measured from an arbitrary luminance I_o. See equation (19).
I_o	An arbitrary luminance level, taken as the origin from which log luminance levels are measured.
Δ (log$I$)	The interval, in logarithmic units, between successive luminance steps.
k	The number of quanta, acting on the retina, required for seeing.
n	The number of presentations at any level.
N	The total number of presentations given in an experiment.
p	The probability of seeing a presentation at any specified luminance.
p'	The probability of guessing correctly the orientation of a test object, or of reporting a blank as 'seen'.
q	$1 - p$.
q'	$1 - p'$.
R	The total number of presentations correctly reported (that is, giving the correct orientation of the test object) or the total number of flashes reported 'seen'. See equation (22).
s	The number of presentations reported 'seen' at any level.
S	The total number of presentations seen in an experiment, corrected for blanks reported 'seen' or test objects reported wrongly orientated.
u	The number of presentations reported 'not seen' at any level ($u = n - s$).
U	$N - S$.
W	The total number of presentations wrongly reported (that is, giving the wrong orientation of the test object) or the total number of flashes reported 'not seen'. See equation (22).
σ	Standard deviation.
σ_m	The standard error of the mean threshold, log I_m. See Table IC.

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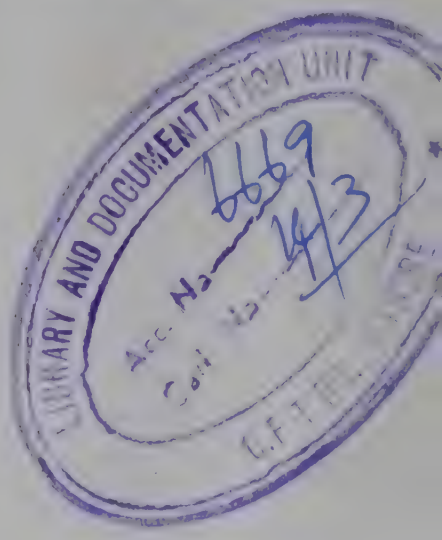

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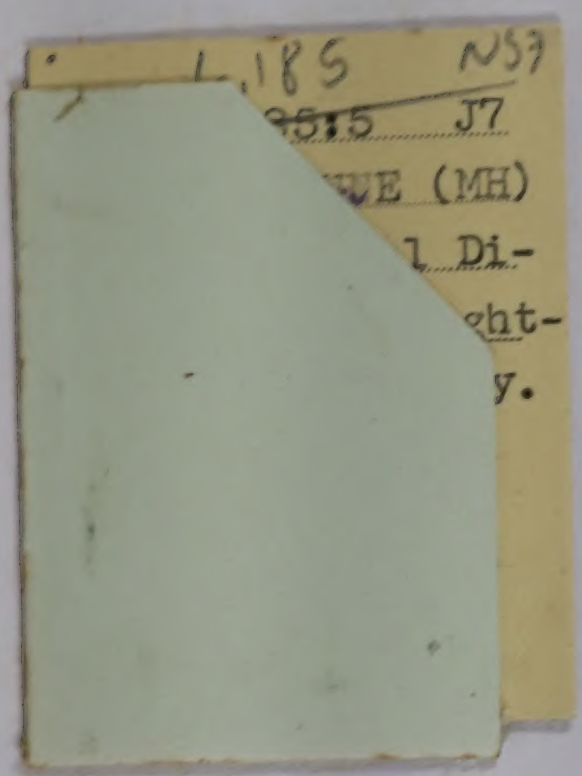
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